IDRC-255e

Solar Drying in Africa

Proceedings of a Workshop held in Dakar, Senegal, 21-24 July 1986

Proceedings

INTERNATIONAL DEVELOPMENT RESEARCH CENTRE · CENTRE DE RECHERCHES POUR LE DÉVELOPPEMENT INTERNATIONAL
CANADA

88-01774/

The International Development Research Centre is a public corporation created by the Parliament of Canada in 1970 to support research designed to adapt science and technology to the needs of developing countries. The Centre's activity is concentrated in six sectors: agriculture, food and nutrition sciences; health sciences; information sciences; social sciences; engineering and earth sciences; and communications. IDRC is financed solely by the Parliament of Canada; its policies, however, are set by an international Board of Governors. The Centre's headquarters are in Ottawa, Canada. Regional offices are located in Africa, Asia, Latin America, and the Middle East.

IDRC-255e

Solar Drying in Africa

Proceedings of a Workshop held in Dakar, Senegal, 21-24 July 1986

Editors: Michael W. Bassey and O.G. Schmidt

© International Development Research Centre 1987
Postal Address: P.O. Box 8500, Ottawa, Ont., Canada K1G 3H9

Bassey, M.W.
Schmidt, O.G.

IDRC, Ottawa CA

IDRC-255e

Solar drying in Africa: proceedings of a workshop held in Dakar, Senegal, 21-24 July 1986. IDRC, Ottawa, Ont., 1987. ix + 286 p. : ill.

/Drying/, /crops/, /solar energy/, /research/, /Africa/ -- /engineering design/, /testing/, /economic aspects/, /social aspects/, /research needs/, /conference reports/, /lists of participants/.

UDC: 631.362.621.47(6)

ISBN: 0-88936-492-3

Technical editors: G.C.R. Croome
Jean-Daniel Dupont

A microfiche edition is available.

Il existe également une édition française de cette publication.

The views expressed are those of the authors and do not necessarily reflect the views of the Centre. Mention of proprietary names does not constitute endorsement of the product and is given only for information.

ABSTRACT / RÉSUMÉ / RESUMEN

Abstract -- This book presents the proceedings of a workshop on solar drying in Africa attended by 24 participants involved with solar drying research relevant to the continent. Of the papers, 17 describe research activities on socioeconomic aspects, design and testing of solar dryers, and future research needs. In addition, a summary of the discussions held during the workshop to assess the state of the art of solar drying research in Africa are outlined, focusing on progress made and on possible research and collaborative activities that are needed to overcome the technical and socioeconomic problems that limit the development and introduction of improved solar dryers.

Résumé -- Voici le compte rendu d'un colloque sur le séchage solaire en Afrique auquel participaient 24 personnes effectuant des travaux de recherche propres à ce continent. Au nombre des communications, 17 décrivent les activités de recherche sur les aspects socio-économiques, la conception et l'essai des séchoirs solaires, ainsi que les besoins futurs de recherche. En outre, le lecteur trouvera un résumé des discussions sur l'état de la recherche sur le séchage solaire en Afrique, notamment les progrès réalisés et les activités de recherche coopératives nécessaires pour surmonter les problèmes techniques et socio-économiques qui entravent la mise au point et la diffusion de séchoirs solaires améliorés.

Resumen -- Este libro contiene los trabajos presentados en un seminario sobre secamiento solar en Africa, al cual asistieron 24 participantes del área de investigación en secamiento solar referida a este continente. Diez y siete de los trabajos versan sobre actividades de investigación en aspectos socioeconómicos, diseño y prueba de secadores solares y necesidades futuras de investigación. Se describe además la discusión sostenida durante el seminario para sopesar el estado de la investigación en secamiento solar en Africa, discusión que se centró en los progresos realizados y en las posibilidades de investigación y acciones colaborativas necesarias para superar los problemas técnicos y socioeconómicos que obstaculizan el desarrollo y la introducción de secadores solares mejorados.

CONTENTS

Foreword vii

Acknowledgments ix

Introduction 1

Discussion and recommendations 6

Potential improvements to traditional solar crop dryers in Cameroon: research and development **Charles J. Minka** 11

Influence of technological factors on the rate of drying of vegetables using solar thermal energy **Emmanuel Tchiengue and Ernest Kaptouom** 23

Outlook for solar drying of fish in the Gambia **A.E. N'Jai** 34

Circulation of air in natural-convection solar dryers **Herick Othieno** 47

Solar energy research for crop drying in Kenya **F.B. Sebbowa** 60

Solar drying in Mali **Modibo Dicko** 75

Potentials and performance studies of solar crop dryers in Mauritius **Y.K.L. Yu Wai Man** 92

Design and tests of solar food dryers in Niger **Yahaya Yaou, Zabeirou Radjikou, and Jean-Marc Durand** 107

Solar energy for crop drying in developing countries **E.A. Arinze** 128

Design, installation, and preliminary testing of a natural-circulation solar-energy tropical-crop dryer **P.D. Fleming, O.V. Ekechukwu, B. Norton, and S.D. Probert** 147

Evaluation of three types of solar dryers for Nigerian crops **J.C. Igbeka** 162

Appropriate technology for solar fish drying in artisanal fishing centres **Niokhor Diouf** 175

Some results from solar drying tests at the Centre national de recherches agronomiques **Hyacinthe Modou Mbengue** 194

Problems and solutions for natural-convection solar crop drying **Michael W. Bassey, Malcolm J.C.C. Whitfield, and Edward Y. Koroma** 207

A numerical model of a natural-convection solar grain dryer: development and validation **P.H. Oosthuizen** 234

Solar drying problems in Togo **K. Amouzou, M. Gnininvi, and B. Kerim** 252

Research and development on solar drying: advancing energy supply options or meeting felt needs **Charles Y. Wereko-Brobby** .. 272

Workshop participants 285

FOREWORD

Because of the importance of drying in the postharvest food system, the Post-Production Systems Group in the Agriculture, Food and Nutrition Sciences Division of the International Development Research Centre (IDRC) has supported several projects on this topic. In addition to the contribution made by other publications on drying, IDRC published Food Drying: Proceedings of a Workshop Held at Edmonton, Alberta, 6-9 July 1981 (IDRC-195e). That publication consisted mainly of the technical research experiences of workers in Africa, Asia, and Latin America on relatively large-scale drying using a variety of energy sources to produce heat. The drying systems considered were, in many respects, representative of the needs of the medium- to large-scale farmer in Asia and Latin America.

As pointed out by Bruce Scott, Director of IDRC's Regional Office in Dakar, in his opening address to the present workshop, the loss of food after harvest represents a significant wastage of existing agricultural production. The development of an appropriate technology to overcome this problem is not unrelated to the vast range of development problems on the African continent. Attempts to develop better preservation methods have shown that such factors as drying requirements, consumer acceptance, commodities to be dried, and heat sources are location specific.

Economic conditions in Africa dictate the use of low-cost drying systems in attempting to improve traditional methods. Thus, solar drying research has been actively pursued by African researchers because solar energy is free and abundant on the continent. Despite all of the research results obtained, however, solar dryers have not yet been effectively introduced for various technical and socioeconomic reasons, as noted for example in the Proceedings of the International Conference on Research and Development of Renewable Energy Technologies in Africa, Mauritius, April 1985, published by Commonwealth Science Council in London, U.K.

Twenty-four participants from 11 African countries, Canada, and the United Kingdom, who were involved in solar drying research relevant to Africa, attended the present workshop, presented papers, and participated in discussions. The outcome of these technical presentations and discussions during various sessions demonstrated that a concerted effort is needed for researchers to relate the needs of the potential user to the design of an improved drying system. Substantial work is needed in the areas of evaluating drying needs, studying dryers on the laboratory scale, and introducing them in the rural areas. Equally, information must be shared among African researchers.

This book should inform the reader of the scope of research being carried out in Africa, explaining the constraints to achieving practical results and how to attempt to overcome them. It is hoped that it will emphasize to researchers in the disciplines of engineering, physics, economics, sociology, and food science and technology that an interdisciplinary approach is needed to develop appropriate solar drying systems.

Finally, we thank all the participants for their contributions during the workshop and the Commonwealth Science Council for the continued collaboration between their African Energy Programme and our Agriculture, Food and Nutrition Sciences Division.

Edward Weber
Associate Director, Post-Production Systems
Agriculture, Food and Nutrition Sciences Division
International Development Research Centre

ACKNOWLEDGMENTS

We wish to express our deepest appreciation to all the participants at the workshop, who contributed to its success by presenting papers, actively participating in discussions, and acting as chairmen or rapporteurs during the various sessions.

Thanks are also extended to Professor Messan Gnininvi, Dr Charles Wereko-Brobby, Mr Gil Croome, and Mr Jean-Daniel Dupont who helped us, as members of the Editorial Committee, to review the papers for this proceedings.

The efforts of Dr Charles Wereko-Brobby in preparing the draft of the summary of recommendations of the workshop are gratefully acknowledged.

Special mention must be made of Messrs Gil Croome and Jean-Daniel Dupont whose efforts have enhanced the final form of all the technical papers. Their professional contributions are highly appreciated.

The workshop would not have been a success without the untiring efforts of Mrs Rose-Marie Erambert and Miss Marie Élisabeth Turpin who were involved from the preparatory activities to the holding of the workshop. We sincerely thank them for their patience and organizational abilities.

The difficult task of discussing highly technical issues among English- and French-speaking participants was simplified by the efficient interpretations of Mrs Joséphine Sarr and Mr Momar Khary Diagne. The accuracy of their translations and the long hours they spent at work are truely appreciated.

INTRODUCTION

The need to dry various foods and cash crops throughout Africa does not have to be justified because the reasons are well known: drying reduces moisture thereby reducing weight, prolongs shelf life, preserves nutritional quality of food, reduces the risk of contamination by toxic moulds, etc. However, traditional open-air drying on the ground is known to suffer from various inadequacies, such as infestation by insects, contamination by dirt and by rodent and bird droppings, and rewetting.

This book addresses the problem of the preservation of food in Africa and improved techniques for harnessing the energy from abundant sunshine for the drying of crops.

Nature of the Drying Problem

The drying problem can be characterized, in a narrow sense, by the following factors:

- Cereal grains and grain legumes, relatively dry crops, need to be dried from an initial moisture content of about 30% at harvest to a level of 12%; by contrast, leafy green vegetables, tomatoes, fruits, fish, and meat have postharvest moisture levels of about 60-80%, which must be reduced to the range of 10-25%.
- Ambient climatic conditions, such as relative humidity (range 30-100%), amount of sunshine (range 2-8 hours/day), available solar radiation (range 10-25 MJ/m^2 per day), frequency and duration of rainshowers during the drying period, dust, and wind, all affect drying rates.
- The subsistence farmer needs to dry relatively small quantities for the family's consumption (1-2 t of grain or grain legumes, 5-50 kg of leafy greens, 5-50 kg of fruit or other perishable foods that mature at the same time and cannot all be consumed at once); the farmer or fisherman whose surplus is destined for distant towns, or for intermediate collection points by cooperative societies must cope with larger quantities (500-1000 kg of fresh fish in the case of the fisherman).

In the larger context, an examination of the food system leads to a precise pinpointing of the location of the drying requirement. In countries with no marketing boards, the drying requirement tends to be at the farm level or at the seaside, or with the trader who is an integral component of the food distribution system; in countries with well-established collection systems for freshly harvested commodities, the major drying requirement may be located at collection depots and long-term storage facilities of the national marketing boards; drying needs in the latter case lie at the level of tonnes rather than kilograms per day, and may include the need for regular redrying of the stored commodities.

Because 80% of Africa's population is rural, the on-farm drying problems at the family level merit the attention of researchers and problem solvers. Similarly, a large proportion of the fish landed in Africa comes from the artisanal sector and is processed by many small-scale operators at the landing site without the benefit of electricity, refrigerated transport, or ice-making equipment.

Evolution of the Research Network

To improve on traditional drying methods, several African researchers have, over the past 10 years, been working on the development of solar dryers for various drying operations. Most of this work has been carried out with each researcher working in isolation, often being unaware of complementary activities taking place in the same country.

African researchers are addressing the problem of food drying in increasing numbers. The research emphasis has evolved from an exclusive focus on dryers as isolated pieces of equipment to the creation of interdisciplinary research teams capable of identifying the dimensions of the drying problem within the larger context of the food system.

In 1977, African researchers identified solar crop drying as an important research theme, in a meeting cosponsored by the Commonwealth Secretariat and the Commonwealth Science Council. Since then, funding for research support has come from a wide range of international agencies. A network of solar crop drying researchers has emerged under the umbrella of the African Energy Programme and has been able to meet at regular intervals. As a result, important research results have been published nationally and internationally (specific references can be found in the papers presented at this workshop).

The April 1985 International Conference on Research and Development of Renewable Energy Technologies in Africa (CSC 1985) is evidence of the quality of scientific work being accomplished now in Africa. It is noteworthy that a substantial proportion of the papers of that conference dealt with the topic of solar crop drying.

The Present Workshop

Although the research effort on solar crop drying has increased substantially, it remains modest in size when compared to the complexity, diversity, and size of the problem. It is not surprising, therefore, that one observes that most of the solar dryers that have been developed either do not perform well or are not accepted by the intended users. The poor performance is mainly because the working air temperature and the airflow through the dryers are poorly matched; the poor acceptance by farmers is generally related to the cost of the drying system and social barriers that were not considered during the technical design stages.

Several constraints have made the task of solar dryer researchers more difficult.

- Solar dryers, for most rural applications, must operate without a fan or blower to circulate the air; thus air flows are inadequate.
- Each commodity has unique drying requirements and it is often inappropriate to use a dryer to dry several crops.
- Potential users usually cannot afford to pay for the dryers.
- The work reported in the literature usually consists of only construction and test results and often lacks information needed to improve on the design or adapt it to another location or crop.
- Fundamental knowledge of how natural flow solar crop dryers behave under operation is generally lacking and good design procedures are absent.

The observations of participants at the April 1985 conference in Mauritius confirmed the urgency of having more discussion among researchers, and the need to better define the strategy for and contents of future work in solar drying.

The present workshop, organized and hosted by IDRC with the cooperation of the Commonwealth Science Council (CSC) who sponsored the attendance of five participants, sought to define the state of solar drying work in Africa and to identify areas for practical research and collaboration that would improve the application of solar energy for crop drying. Specifically, the workshop aimed to achieve the following outcomes:

- To critically review the research that has been carried out on solar drying in Africa;
- To identify the main technical obstacles that have affected the design and operation of solar crop dryers and recommend methods for overcoming them;
- To recommend, if possible, viable technologies for drying;
- To identify socioeconomic factors that affect the introduction of solar dryers in rural areas and recommend corrective procedures;
- To set priorities for future research and development work on crop drying (development and implementation activities); and
- To set in place a mechanism for improving the collaboration among researchers in crop drying.

The workshop took place in two stages. First, the papers were briefly presented by the authors who were subjected to questions from the participants. (The papers form the final section of these proceedings.) Second, in a series of four round-table discussions, participants identified:

- Technical problems, gaps, and research needs;

- The socioeconomic framework within which future research should be conducted;
- Strategies for linking research efforts and results with implementation and development programs; and
- Opportunities for improving collaboration among scientists to achieve maximum impact from the sparse research resources available in each country.

Overview of the Papers

The following chapter, "Discussion and Recommendations," presents a useful contextual framework for the major issues identified, and presents the specific recommendations made by the participants.

With a few exceptions, the papers fall into two broad categories. One group of authors is primarily user-oriented, and presents research that is conducted principally in the domain of the user, identifying the dryer hardware as a potential means for improving quality or preservation of a food product. The emphasis is on drying problems. The papers by Minka of Cameroon, N'Jai of The Gambia, and Diouf of Senegal are representative of this category. The second group of authors tends to deal with particular hardware configurations, and presents performance data that have usually been acquired under laboratory or research station conditions: the emphasis is on dryers. In general, one finds that the user-led researcher often tends to treat specific technical issues too lightly, resulting in insufficient reporting of data relating to, say, engineering or food science. Conversely, the researcher who emphasizes the hardware can almost appear to be presenting solutions that are in search of their problems. It is interesting to note that these respective strengths of research emphasis, and the logic of combining forces to solve a total problem, did not receive much emphasis during the discussion on collaboration.

The paper by Bassey et al. is particularly instructive and represents a welcome addition to the literature. The paper details a complete research process beginning with the identification of a user-problem, includes the generation of a technical design, and ends with the "proving" of that design in the user domain. The paper is particularly explicit in identifying the authors' perceptions of shortcomings in the total research process.

A critical examination of the research literature in solar drying leads to the hypothesis that some of the work reported lacks a linkage to theoretical analysis. Thus, one finds researchers abandoning a particular design on the basis of limited (and often disappointing) performance results, in favour of a new design, but in the absence of a clearly documented analysis of the reasons for the abandonment. As well, one sees some evidence of apparently random alteration of certain design parameters, without reference to a theoretical analysis.

A significant contribution, therefore, to the research landscape is the following convergence among theory, design, and testing of prototypes. There appears to be a general conclusion that low airflow rates constitute the limiting condition for natural convection solar dryers. The technical addition of an electrically or engine driven fan is either not feasible in many rural areas due to absence of electrification or is financially prohibitive in the case of petrol- or diesel-driven fans. The paper by Oosthuizen identifies the role of theoretical analysis and of modeling techniques as a promising research contribution to the field. This theme is strongly reflected in the next chapter.

Wereko-Brobby presents the engineer with the central question: are you sure that you are working on the correct problem? His paper emphasizes the need for multidisciplinary research teams if the user is to derive any real benefits, and points to the need to adopt and improve socioeconomic methodologies. His paper underlines the often repeated (and often neglected) statement that an improved hardware or technology, to be adoptable, must demonstrate technical soundness, social acceptability, and economic viability.

Amouzou et al. of Togo indicate that a major drying problem lies at the larger-scale level. Their paper illustrates that correctly locating the drying problem in the postharvest sequence guides the scope and emphasis of technical research.

Minka of Cameroon shows the importance of defining the drying problem in the user context and suggests that issues such as dirt exclusion and the ability to leave the dryer unattended while the user is active on other chores may be far more important than the reduction of drying times. His interpretation of experimental results challenges the engineer to acknowledge that hard measures such as drying efficiency may need to take second place to other considerations in certain contexts.

Bassey et al., in a portion of their paper, underline the importance of augmenting the sun's ability to dry under overcast conditions by introducing a hybrid dryer and give a practical example of how agricultural waste material may be used in such dryers.

Finally, Sebbowa of Kenya raises some important issues of the policy climate, which can clearly support or constrain successful research for development.

The wide range of products being dried by researchers will also be of interest to the reader. They range through grains, leafy green vegetables, meat products, fish, boiled plantains, and pyrethrum. The common interest in better compilation of drying characteristics is addressed in the next chapter.

In general, the technical papers illustrate the wide range of solar drying activities that have taken place in Africa, pointing out the gaps that need to be filled.

Reference

CSC (Commonwealth Science Council). 1985. Renewable energy developments in Africa: Proceedings of the International Conference on Research and Development of Renewable Energy Technologies in Africa, Mauritius, 25 March - 1 April 1985 (2 vols). CSC, London, U.K.

DISCUSSION AND RECOMMENDATIONS

General Framework

The development of solar crop dryers, like most other problem-oriented research and development (R&D) activities, faces the primary task of evolving and applying a coherent problem-solving procedure that ensures both correct identification of the problem as well as appropriate and acceptable solutions for the target clients. The essential elements and conceptual approach for such a procedure might take the form shown in Fig. 1.

In their discussions, the researchers addressed the problem-solving procedure by examining three questions:

- What are the major problems (technical and socioeconomic) still to be tackled and how should they be defined?
- What should researchers do to find appropriate solutions and how should they do it?
- How could the solutions be made available to the target clients?

The group concluded that three areas of research activity require emphasis and strengthening:

- Socioeconomics: improved research techniques and methodologies are needed to better identify the user's problem, to evaluate the appropriateness of potential technical solutions, and to assess the socioeconomic acceptability of final solutions; there is also a need to develop a common vocabulary between the natural and applied sciences on the one hand and the social sciences on the other.
- Experimentation: modeling and testing of dryer hardware must be improved; dryer performance must be matched to the drying characteristics of the product; more work is needed regarding baseline drying characteristics of common food commodities; optimization techniques for system components and for the whole drying system must be developed to include optimization for dryer-commodity interactions.
- Implementation/dissemination: to bring an acceptable solution into widespread use, attention must be paid to the following steps; proving the durability and acceptability of a useful design in the user's domain by interaction with end users and providing entrepreneurial opportunities for manufacture and distribution;

It was recognized that the priority tasks for applied researchers at the moment relate to the socioeconomic area and to experimentation.

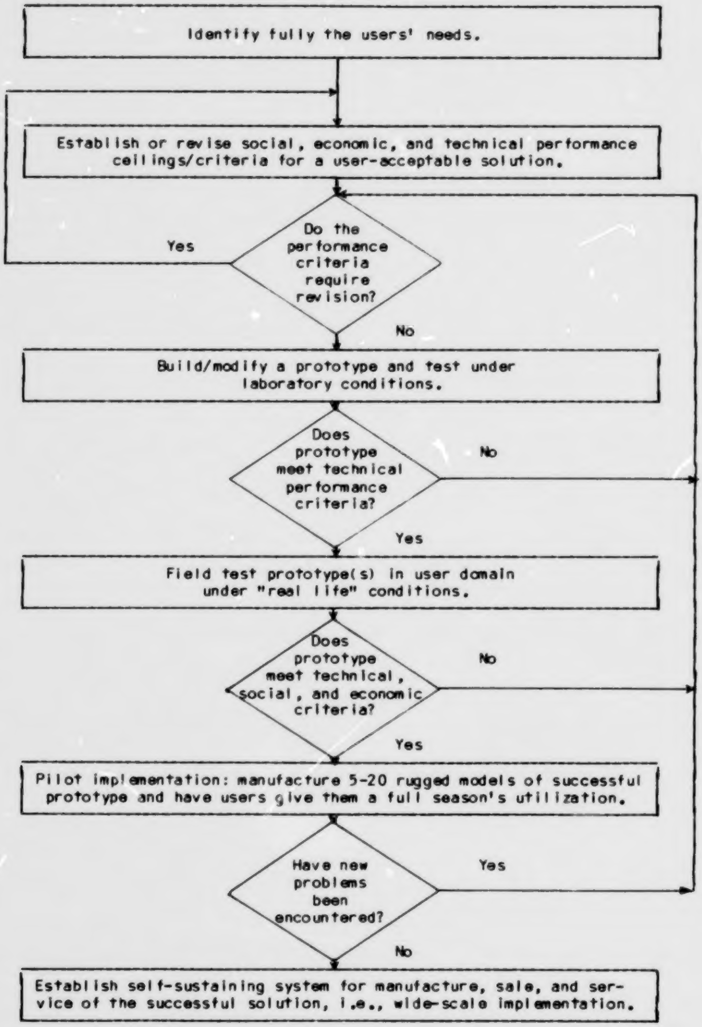

Identify fully the users' needs.
Establish or revise social, economic, and technical performance ceilings/criteria for a user-acceptable solution.
Do the performance criteria require revision?
Yes
No
Build/modify a prototype and test under laboratory conditions.
Does prototype meet technical performance criteria?
No
Yes
Field test prototype(s) in user domain under "real life" conditions.
Does prototype meet technical, social, and economic criteria?
No
Yes
Pilot implementation: manufacture 5-20 rugged models of successful prototype and have users give them a full season's utilization.
Have new problems been encountered?
Yes
No
Establish self-sustaining system for manufacture, sale, and service of the successful solution, i.e., wide-scale implementation.

Fig. 1. Flowchart of the applied research process for technology development in response to user needs.

Emphasis on more effective research processes in these two areas will generate solutions that will match more closely the user's needs. Increased emphasis can then be placed on implementation and dissemination.

Major Problems

In their discussions of the four key themes, researchers identified the following problems and constraints that have characterized past research on solar drying.

1. Technical problems, gaps, and research needs

- The absence of a sequential technical design procedure;
- The inadequacy of existing testing and monitoring procedures; and
- The need to evolve a common method for evaluation and comparison of final products (dryer designs).

2. Socioeconomic aspects

- Failure to set solar dryer technology development in the context of an overall drying problem;
- Failure to identify the specific elements of the socioeconomic context, including: identifying user problems, establishing a basis for evaluation, and developing methodologies for appraisal;
- Failure to establish the relative priority of drying in the national food postproduction system (i.e., are storage problems more important than drying problems?).

3. Linkage between R&D and implementation

Despite the experience of several years of experimentation, there are still few operational dryers in the field. The bulk of effort still seems to be bogged down in the area of fundamental organization and optimization of various dryer components and systems. Linkages must be established to relate laboratory research to the need to solve real and pressing developmental problems.

There is little interaction between researchers, end-users, and extension workers during the development and proving of dryers. This often leads to the design of inappropriate technologies of limited relevance to the ultimate consumers.

4. Collaboration among scientists

It is generally recognized that African researchers need to collaborate, both in research activities and in exchange of shared experiences. However, some very real problems limit such cooperation:

- Inadequate access to information on past and present work in Africa and elsewhere leading to duplication of effort and isolation of researchers;
- Lack of collaboration among researchers within countries, both within one subject area and between subject areas where interaction is needed to address specific problems; and
- Lack of contact among researchers between countries working in a

single subject area or in different disciplines that are relevant to their own concerns.

The most urgent problem, however, appears to be a distinct lack of willingness of researchers to collaborate. This is especially evident in the failure to support attempts to establish and sustain African learned societies and journals through prompt payment of subscriptions, contribution of technical papers for publication, and assistance with organizational and editorial functions. Because the researchers' general unwillingness to collaborate may stem from a fear of losing control of "their" data, a channel through which to publish individually recognized output is urgently needed.

Recommendations

The recommendations can best be grouped into those that concern the topics of future R&D emphasis and those that relate to improved collaboration among researchers.

Research and Development

Technical Issues

A comprehensive design procedure for solar crop dryers must be developed. This should attempt to provide a step-by-step guide to practitioners to the specific tasks and requirements of the process outlined in Fig. 1. Given the enormous amount of work already carried out in solar dryer experimentation, an essential component of such an exercise should be the provision of information and up-to-date source references (such as the CSC Handbook 1985).

A rigorous program must be established for performance testing, monitoring, and evaluation. This should include, inter-alia:

- Developing better modeling techniques;
- Matching modeling to field experimentation;
- Providing adequate instrumentation to ensure continuous monitoring;
- Establishing performance descriptors for traditional drying as baselines for comparative technical assessment and evaluation; and
- Improving airflow through dryers by better design of chimneys and incorporation of other devices.

Base line data on must be established for characteristics of the major crops in Africa. This should include physical indicators such as desired moisture content and temperature, and physiological and microbiological relationships and their impact on postharvest losses as well as on nutritional quality.

It is also important to establish data on the postdrying characteristics of the various products, especially the requirements for storage to minimize further loss and retain nutritional value.

Socioeconomic Issues

Methodologies must be developed for identifying user problems and assessing the economic profitability of various dryer designs in specific sociocultural environments. The user identification methodology should address three specific areas of postharvest investigation and target the relevant user-groups.

The postharvest aspect should include estimation of product quantity, losses, and relative importance of drying. At the same time, the targeting of user-groups should include assessment of existing drying machines, product types, market and price relationships, income distribution, and the alternatives to solar dryers.

The economic appraisal methodology should concentrate on establishing techniques for qualifying the specific impacts of intangibles, such as improved health and quality of life, on the technoeconomic feasibility of solar dryers. Procedures are already well established for the economic appraisal of profitability when dealing with individuals or businesses. However, data for some important economic indicators, such as discount rate and shadow prices, must be improved to assist better financial appraisal.

Collaboration

To ensure an effective start to collaboration among African researchers, the following are recommended for immediate action:

- Each researcher is requested to compile a complete listing of the members of their research team and of other related research teams in their establishment (if they exist). The completed list should be sent to the workshop organizers for compilation and dissemination to the group.
- On the assumption that there are projected commitments of financial assistance for the publication of a journal on renewable energy R&D in Africa, it is recommended that the African Solar Energy Society establish an editorial board as soon as possible and that this board be charged with the task of developing an editorial policy and publishing the journal as an independent medium of reportage of important research results. Crop drying researchers could be encouraged to facilitate the process by offering to provide the services of one of their members as a technical editor for post-production systems.
- A committee should be established to explore the feasibility of producing a journal of post-production R&D in Africa. Should the journal's feasibility and viability be established, the committee should aim to publish the first issue within the next 12-18 months.
- The continued collaboration of international donor agencies such as IDRC and CSC with the research organizations in each of the African countries should be encouraged.

POTENTIAL IMPROVEMENTS TO TRADITIONAL SOLAR CROP DRYERS IN CAMEROON: RESEARCH AND DEVELOPMENT

Charles J. Minka[1]

Abstract *-- Sun dryers used by small farmers in Cameroon have been evaluated. These included bamboo mats elevated on posts, cement courts, and corrugated aluminum sheets laid on the ground. The performance of these traditional dryers was compared to that of simple direct solar dryers: marquee and cabinet dryers. Drying times for various agricultural produce (cacao, maize, groundnuts, and plantain) were measured and efficiencies of the different dryers determined. The results of laboratory and field tests showed that the efficiencies of the different traditional sun dryers are essentially the same and that natural-convection direct solar dryers, in most cases, do not significantly reduce drying times as compared with sun dryers. However, the solar dryers are useful under adverse environmental conditions (dust, rain, and animals). Design and operation problems of agricultural solar dryers are discussed and recommendations made regarding future research and development work and ways of intensifying collaboration among solar drying researchers.*

Introduction

Drying has been and continues to be a major method of preserving agricultural products in Cameroon. It is generally carried out by direct exposure of the produce to solar radiation. The produce may be spread directly on the ground, on a mat, or on a cement court.

The disadvantages associated with these traditional sun dryers are well known. Drying is slow and sometimes incomplete under unfavourable climatological conditions. Constant supervision of the dryer is necessary as the produce must be gathered and moved under cover in the event of rain and predators must be chased away. The produce is subjected to noxious effects of dust, dirt, and insect infestation.

Thus, this method of drying needs improvement if produce suitable for prolonged storage is to be obtained. However, when considering more efficient dryers, the socioeconomic conditions of the users must always be kept in mind. In Cameroon, 90% of food and cash crops are produced by small farmers who also carry out drying operations. These farmers cannot afford to invest much on a dryer because drying is only one part of the production-consumption chain. In fact, if sun drying remains popular among small farmers, it is mainly because it is cheap: the dryer is built by the farmer and the energy source is free.

---

[1] National Center for Studies and Experimentation in Agricultural Mechanization (CENEEMA, Centre national d'études et d'expérimentation du machinisme agricole), Department of Renewable Energy, B.P. 1040, Yaoundé, Cameroon.

In Cameroon, two institutions are now involved in work on solar drying: the National Polytechnic Institute of Yaoundé (ENSPY, École Nationale Supérieure Polytechnique de Yaoundé) and the National Center for Studies and Experimentation in Agricultural Mechanization (CENEEMA, Centre national d'études et d'expérimentation du machinisme agricole).

At ENSPY, the mathematical modeling of solar collectors for indirect solar dryers using natural convection has been studied (Lefevre 1983). CENEEMA has concentrated its efforts on the construction and testing of various solar dryers and it is this work that is reported here.

Crops Dried and Prevailing Climatological Conditions

The major crops dried are cacao, coffee, tobacco, groundnuts, and maize in the southern part of Cameroon and groundnuts and sorghum in the northern part.

These crops are dried in June to July and November to January in the south, and November to December in the north with the drying period coinciding with the dry season.

Climatological conditions are more favourable for solar drying in the north than in the south (Table 1). The laboratory and field tests of solar dryers presented here were carried out in the south.

Experiments

Types of Dryers

Because crops are dried mainly by small farmers in Cameroon, CENEEMA, whose object is to develop agricultural implements adapted to local socioeconomic conditions, has so far limited its studies to simple solar dryers that are easy to construct, operate, and maintain,

Table 1. Prevailing conditions for solar crop drying in Cameroon during the drying periods.

	South	**North**
Temperature (°C)	22-30	22-40
Relative humidity (%)	50-100	20-40
Average solar radiation (kWh/m^2 per day)	3·8	5·5
Sunshine (hours/day)	3-6	7-9

and that are financially accessible to the farmers. The three dryers tested were traditional sun dryers, marquee dryers, and cabinet dryers.

Traditional Sun Dryers

Traditional sun dryers consist simply of any suitable drying surface exposed to solar radiation, for example, a bamboo mat laid on the ground or on posts (Fig. 1), a corrugated aluminum sheet, a cement court, or just the bare ground.

Marquee Dryers

A marquee dryer consists of a drying platform covered by a transparent structure. Solar radiation can reach the crop being dried and, at the same time, the latter is protected from rain, dust, and predators. The prototype tested (Figs. 2 and 3) has two parallel drying platforms elevated on posts and separated by a central passage for the operator. The platforms and the central passage are covered with a transparent plastic film attached to a wooden structure with sloping roof. The drying surface may be made of wire screens, bamboo mats, or corrugated aluminum sheets laid over wooden beams across the platform. Air passages are provided at the lower and upper edges of the roof.

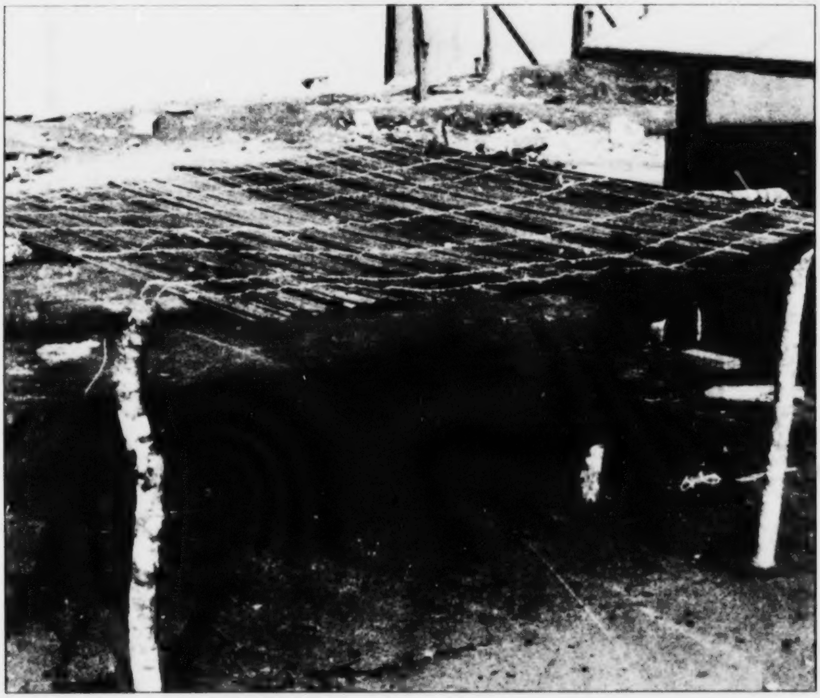


Fig. 1. The bamboo mat sun dryer elevated on posts.

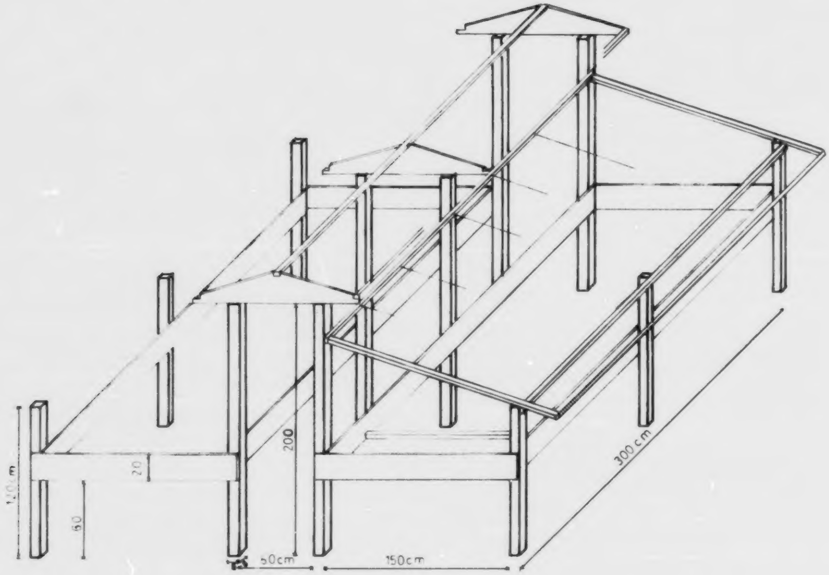


Fig. 2. Plan of the marquee dryer.

Another prototype of the marquee dryer (Fig. 3b) is now being tested. It consists of one platform. Doors made of plywood are provided at the rear, with their inner sides painted black.

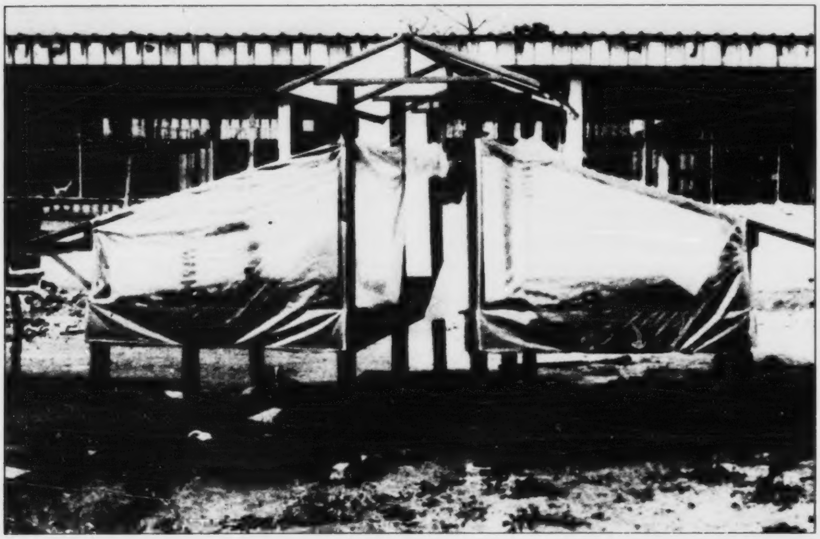
Cabinet Dryers

The cabinet dryer tested (Fig. 4) is of the type pioneered by the Brace Research Institute in Canada (Anon. 1965). It is essentially a rectangular container insulated at its base and covered with a glass or clear plastic roof. Holes drilled through the base permit fresh air to enter the cabinet. Outlet holes are located on the upper parts of the cabinet side and rear panels. In this case, the cabinet was constructed of 19-mm thick plywood panels.

Design Procedure

The dryers studied were simple direct natural convection dryers. No thermodynamic studies or computer modeling techniques were used in the design of the prototypes tested. However, a number of technical and socioeconomic factors were taken into account: the nature of the commodity, the size of the batches to be dried, the availability and cost of construction materials, the level of expertise needed to construct and maintain the dryer, and the ease of operation.

With this design procedure, it is not possible to predict dryer performance under various operating conditions.



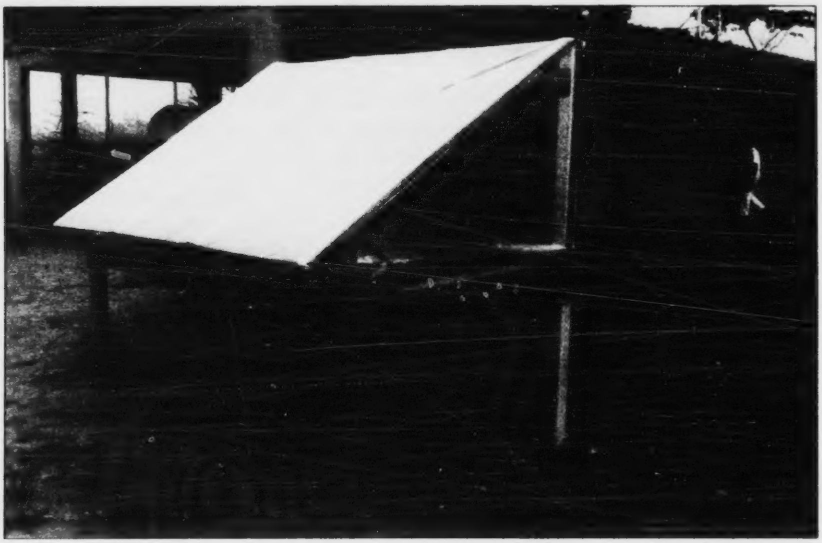


Fig. 3. Two marquee dryers.

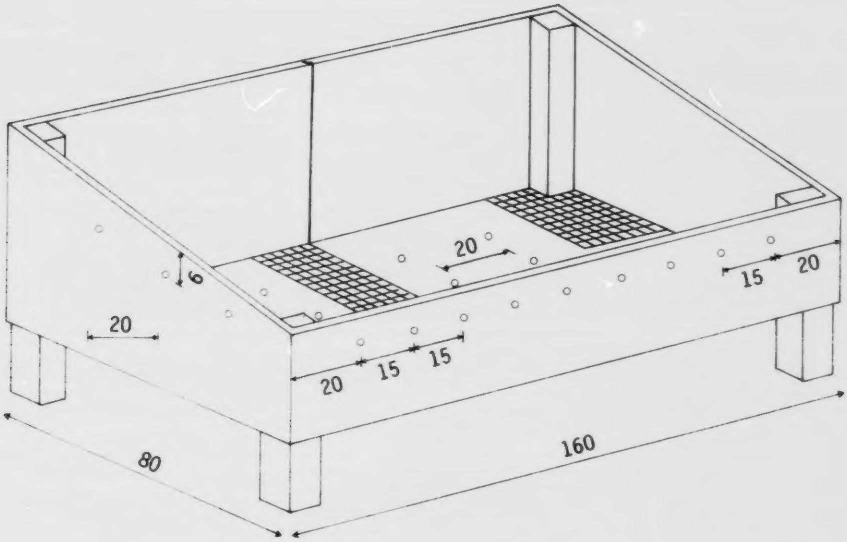


Fig. 4. Solar cabinet dryer (dimensions in centimetres).

Laboratory Experiments

Five series of experiments were carried out, involving traditional sun dryers, traditional sun dryers covered with clear plastic roofs, marquee dryers, and cabinet dryers.

In the first experiment, three types of traditional sun dryers, a bamboo mat elevated on posts, a corrugated aluminum sheet laid on the ground, and a cement court, were compared. The product dried was boiled plantain at a loading density of 17 kg/m^2 of wet plantain (61% wet basis) and the operating conditions were as shown in Table 2.

In experiment two, sun dryers covered with a moveable clear plastic roof were compared. Such covers could be useful in case of sudden rainfall. The dryers were the same as in the first experiment and the operating conditions were also similar.

In the third experiment, the performance of a marquee dryer with a wire screen supporting surface was compared with that of a traditional bamboo mat sun dryer. The products dried were cacao, groundnuts, and maize. The loading densities for each dryer were 10 kg/m^2 of dry cacao (8% moisture content, wet basis). 2 kg/m^2 of groundnuts (10% moisture content), and 4 kg/m^2 of dry maize (10% moisture content). The operating conditions were somewhat more favourable than for the first experiment (Table 2).

Experiment four was to compare three types of drying surfaces in a marquee dryer: bamboo mats, wire screen, and corrugated aluminum sheets. Cacao, groundnut, and maize were dried and the loading densities on all three surfaces were the same as in the third experiment as were the operating conditions.

In the fifth experiment, the performances of a marquee dryer, a cabinet dryer, and a traditional sun dryer were compared. Slices of boiled plantain were dried at a loading density of 15 kg/m^2 (61% moisture content, wet basis) under operating conditions that were less favourable than the first experiment (Table 2).

Results

The first series of experiments indicated that all three sun dryers have practically the same drying efficiency (Table 3). This may be explained by the fact that these dryers differ only in the nature of their drying surfaces, which only serve as supports to the produce and do not affect the drying process, which depends mainly on incident solar radiation. Thus, the choice among these dryers cannot

Table 2. Operating conditions during the laboratory experiments.

	Experiment		
	1 and 2	**3 and 4**	**5**
Temperature (°C)	23-32	25-35	22-30
Relative humidity (%)	50-100	55-100	65-100
Average solar radiation (kWh/m^2 per day)	3·5	4·1	3·8
Sunshine (hours/day)	3-4	4-6	4-5

Table 3. Drying efficiencies[a] for boiled plantain of traditional sun dryers with or without transparent plastic roofs.

	Efficiency (%)	
Dryer	**No roof**	**With roof**
Bamboo mat	15.0	14.5
Cement court	14.0	15.0
Corrugated aluminum sheet	13.5	14.0

[a] Efficiency is defined as: (useful energy to dry the produce to a given moisture content)/(total energy input into the dryer).

be based on drying efficiency, it must be based on the availability of construction materials and the durability and cost of the dryer.

Even when covered with a transparent roof, as in the second experiment, the three traditional sun dryers have the same drying efficiency as each other (Table 3), and as compared with the dryers with no cover. Apparently, covering traditional sun dryers with transparent roofs only helps to protect the produce against rain and animals; it does not increase drying rates. In fact, the temperature of the air inside the covered dryer was higher than ambient tempera-

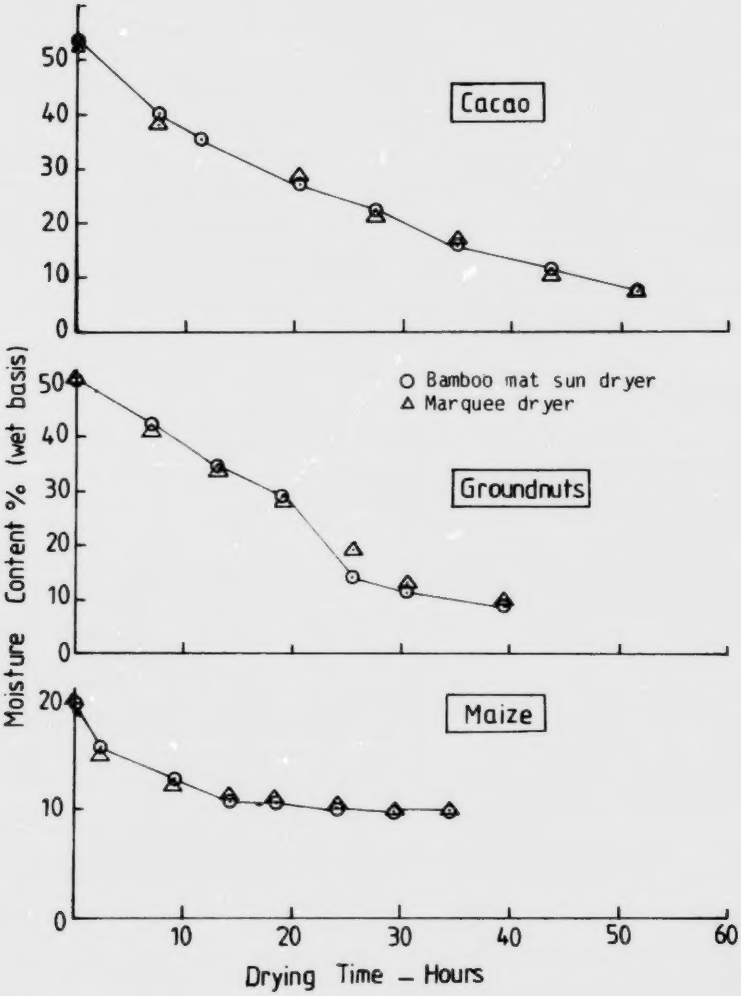


Fig. 5. Comparative drying curves of three products for two different drying systems.

ture, but its relative humidity was also higher, especially in the early stages of drying.

Drying rates of cacao, groundnuts, and maize in the third experiment were the same in the marquee dryer with a wire screen support as in the traditional sun dryer (Fig. 5). This result is not surprising as the marquee dryer is essentially a covered traditional sun dryer. However, when the supporting surface in the marquee dryer was varied, as in the fourth experiment, there was a crop-specific difference in drying rate (Fig. 6). Apparently, the corrugated aluminum sheet does

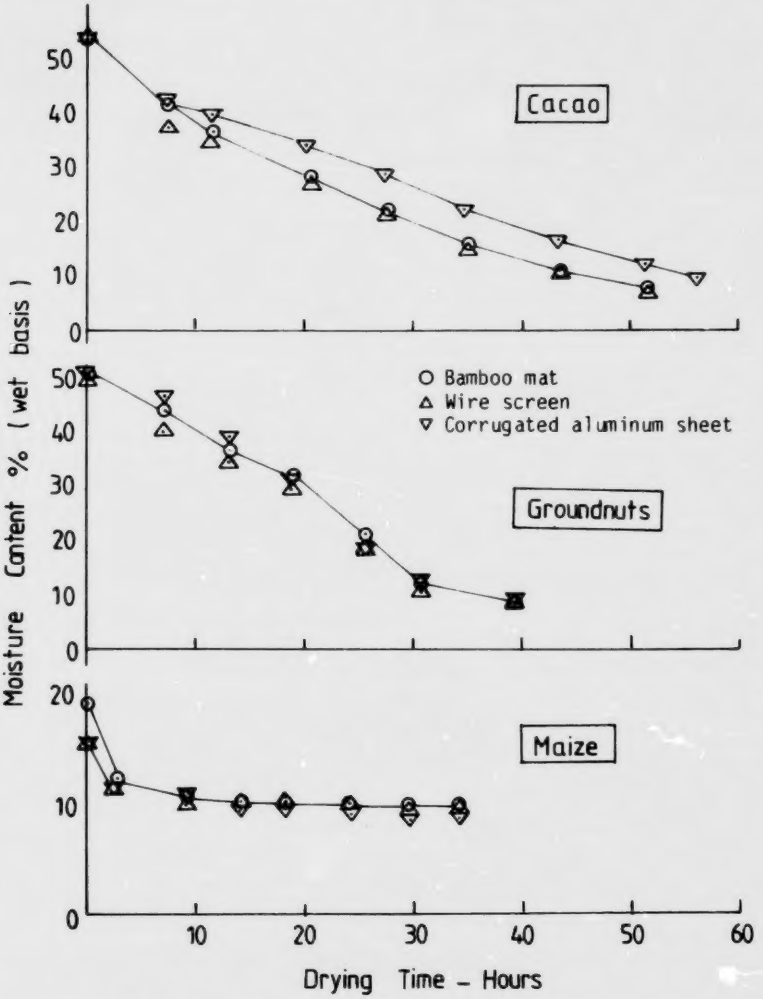


Fig. 6. Comparative drying curves of three products for different drying surfaces in a marquee dryer.

not allow the cacao to drain, as occurs on the bamboo and wire supports, so that drying is slower. However, bamboo mats were as efficient as wire screens, thus the bamboo may be used in place of the wire, which is quite expensive in Cameroon.

Where the performance of a cabinet dryer was compared to those of a marquee dryer and a traditional sun dryer, in the fifth experiment, the drying rate of boiled slices of plantain was much higher in the cabinet dryer than in the other two dryers (Fig. 7). Temperatures reached in the cabinet dryer were 20-30°C above ambient temperature. The cabinet dryer should be useful in drying a variety of foodstuff.

Field Tests

Marquee dryers of the same size as the laboratory prototypes have been installed in various farms for field tests. They have been used by farmers for drying various products (cacao, groundnuts, manioc flour, spices, and herbs) for almost 1 year. These dryers were built by local carpenters using detailed drawings provided by CENEEMA and under the supervision of CENEEMA technicians.

The response of farmers involved in the tests has been favour-

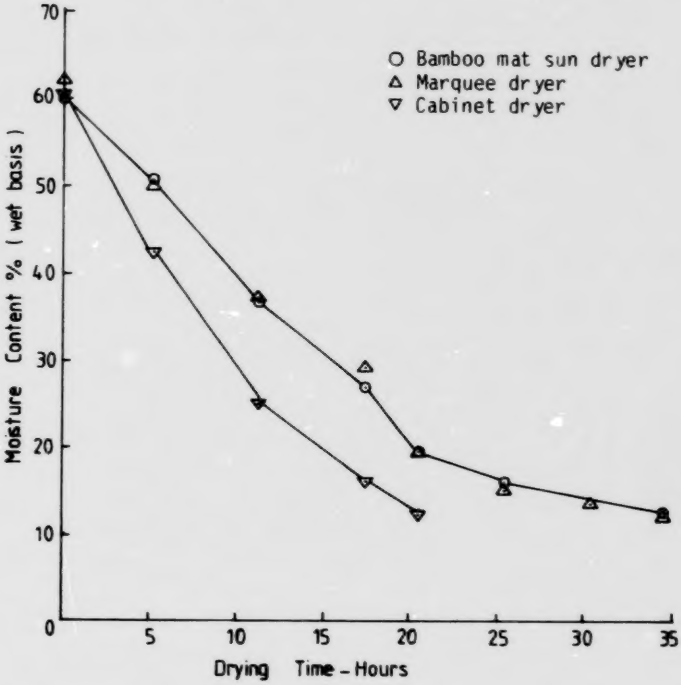


Fig. 7. Comparative drying curves of boiled plantain for different drying systems.

able. Asked to compare the marquee dryer to their traditional sun dryers, some farmers reported a slight gain in drying time and others found the dried product to be of better quality. To all of them, a reduction in drying time was not a major concern; however, protection of the product against rain, dust, and animals was what counted most. The only drawback often mentioned was the poor durability of the plastic material used to cover the dryers. It was polyethylene packaging sheets, which are easily found on the local market, but which were damaged by sun rays and strong winds after 4-6 months on the dryer.

Two cabinet dryers were also field tested. One was used to dry ndole leaves and the other yam flour. With ndole leaves, drying time was reduced by 50%. For yam flour, however, the gain in drying time was not significant because the transparent cover fogged up during the early stages of drying. To overcome this, the doors of the dryer had to be left open, reducing the efficiency of the dryer. It may be necessary to determine optimal loading densities of this dryer for various products.

Design and Operation Problems

From our laboratory and field experience, four major technical obstacles were found that affect the design and operation of solar dryers intended for rural areas:

- The necessity to limit oneself to natural ventilation; this is a serious constraint if one intends to obtain high drying rates.
- The lack of knowledge of pertinent physical and chemical properties of the commodity being dried: the characteristics required for a good quality end product and the optimal drying conditions are often unknown.
- The lack of data on the effects of the various design parameters on the behaviour of the dryers.
- The absence of a universal criterion for evaluating the performance of solar dryers: one is reduced to comparing different dryers operating under the same conditions. Thus, the drying efficiencies depend on so many uncontrolled factors that they are almost meaningless.

Of the socioeconomic factors, the most important is the high initial cost of solar dryers. This, for small farmers, may not be offset by future financial gains.

Recommendations

In designing solar dryers for rural areas, the limited financial resources of most farmers should always be kept in mind. A reduction in drying time is not necessarily what they are looking for. Improvement in quality of dried products and labour reduction may be more important to them. Accordingly, simple direct solar dryers, easily constructed with readily, and cheaply, available materials may be all that is needed. The solar dryers tested at CENEEMA seem promising, although the need for improvement was clear on the basis of the field tests. Only in the case of large installations with high throughputs should indirect solar dryers with forced convection be considered. Natural convection indirect dryers seldom achieve high drying rates.

Future research and development work on solar dryers in Cameroon should include:

- The intensification of field tests of marquee and cabinet dryers and the improvement of the dryers on the basis of users' reactions;
- The development of direct solar dryers with auxilliary heat sources;
- The experimental study of the effect of various design parameters on the technical performance of direct solar dryers; and
- The development of procedures to evaluate the technical performance of solar dryers.

References

Anon. 1965. How to make a solar cabinet dryer for agricultural produce. Brace Research Institute, Sainte Anne de Bellevue, Canada. Do-it-Yourself Leaflet L6. 9 pp.

Lefevre, A. 1983. Modélisation du capteur plan à air et application au séchage de produits agricoles. Institut national des sciences appliquées de Lyon, France. PhD thesis.

INFLUENCE OF TECHNOLOGICAL FACTORS ON THE RATE OF DRYING OF VEGETABLES USING SOLAR THERMAL ENERGY

Emmanuel Tchiengue and Ernest Kaptouom[1]

Abstract -- *Leafy green vegetables were prepared by the traditional method used in Cameroon. Young leaves of Amaranthus hybridus, either cut or whole, were washed in water, blanched in boiling water for various periods, squeezed dry, and left to dry in layers of various densities under various ambient conditions.*

The drying rate of vegetables depends largely on the preparation procedures that are used: blanching time, dimensions of the particles and agglomerates of particles, spreading density of vegetables on the racks, time of day at which drying starts, etc. The drying rate is optimum when the vegetables have been blanched whole for 7-10 minutes in water at 100 °C and placed in the indirect solar dryer at 0700 hours, with a spreading density of 3-6.5 kg/m^2. The drying time to achieve a final moisture content of 10.5-12.0% varies from 4 to 10 hours. At an optimum density of 3 kg/m^2, the drying cycle can be completed in 1 day under favourable atmospheric conditions. For the Yaoundé site, when the drying time is more than 4 hours, the actual time needed for drying products rises from 4 to at least 28 hours depending on the daily duration of sunshine.

Organoleptic qualities of the vegetables were not changed when they were stored in plastic wrapping for 6-8 months at ambient temperature. After reconstitution, the product's natural green colour and fresh vegetable qualities were restored. No additive was necessary.

Introduction

In Cameroon, the term ndolé refers both to the vegetables themselves and to the dishes that are prepared from them using traditional procedures. The most popular leafy green vegetables include Vernonai amygdalina, Amaranthus hybridus, and Hibiscus cannabinus.

In some regions of the country, average daily consumption of vegetables is as high as 64 g/person, or 5.4% by weight of all foodstuffs consumed (Masseyeff 1958). For people in rural areas, vegetables are an excellent source of protein, as well as vitamins and mineral salts. Because of a high starch availability (manioc, macabo, plantain, and cereals), these vegetables also contribute an indispensable dietary supplement of cellulose bulk that, in reasonable quantities, ensures regular functioning of the intestinal tract. These vegetables tend to compensate for the malnutrition suffered by peoples in vast regions of Africa.

---

[1] Laboratoire de mécanique et énergétique de l'École nationale supérieure polytechnique, University of Yaoundé, Cameroon.

Although these vegetables have been prepared by traditional methods for several centuries, no industrial initiatives have so far been taken to mechanize the process. Little research has been conducted on processing technologies for these vegetables. Given their seasonal nature, it would seem vital to develop industrial processing technologies for these vegetables so as to ensure greater availability and the potential for year-round consumption.

In Cameroon, vegetables are usually dried in regions where atmospheric conditions permit, and particularly in those regions that have long dry periods, such as the western High Plateau, Adamaoua, and the north of the country (Tchiengue and Kaptououm 1983).

The leaves to be dried are generally picked individually, cut, washed, boiled in water (with or without added rock salt), rewashed, and placed to dry on racks exposed to solar radiation or suspended over a wood fire.

Some researchers have studied the chemical composition of the vegetables or the prepared ndolés (Masseyeff 1958; Fournier 1979). To our knowledge, however, no systematic study has been carried out to adapt or develop technologies for producing dried vegetables using solar thermal energy with specific equipment under tropical conditions.

This paper presents the results of research on the main technological factors that influence the drying rate of vegetables. The development of a model dryer should facilitate further research, particularly on technological processes that are viable from an industrial and economic standpoint and are suited to the modest size of the small industries in African countries.

Equipment and Methods

The technological process of drying agricultural products must be undertaken under defined conditions of air temperature and relative humidity if the dried product is to be well preserved. During the drying process, the air parameters and the product characteristics vary according to laws that may be either simple or complex.

Measurements of the drying characteristics of ndolé required a specially constructed chamber for regulating air temperature and humidity (Fig. 1). The mass loss of the product was measured with a recording balance as a function of time under given conditions of temperature and humidity. Because the theoretical and experimental results agreed well, we proceeded with experiments in a solar dryer (Figs 2 and 3).

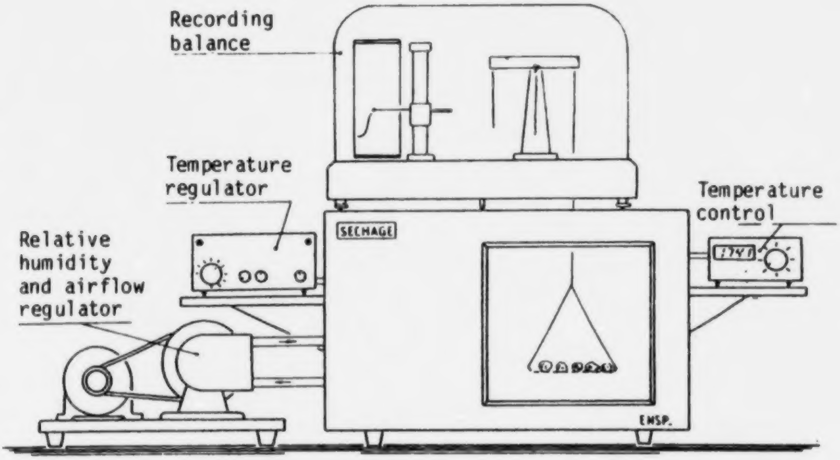

Recording balance
Temperature regulator
Relative humidity and airflow regulator
Temperature control
SECHAGE
ENSP.

Fig. 1. Construction of drying chamber.

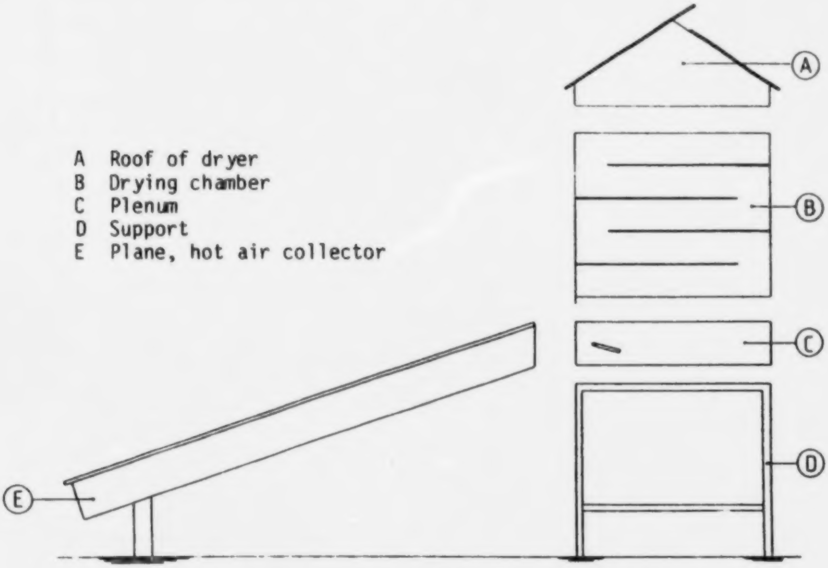

A Roof of dryer
B Drying chamber
C Plenum
D Support
E Plane, hot air collector
A
B
C
D
E

Fig. 2. Experimental dryer assembly.

The experimental dryer shown in Fig. 3 has the following technical description:

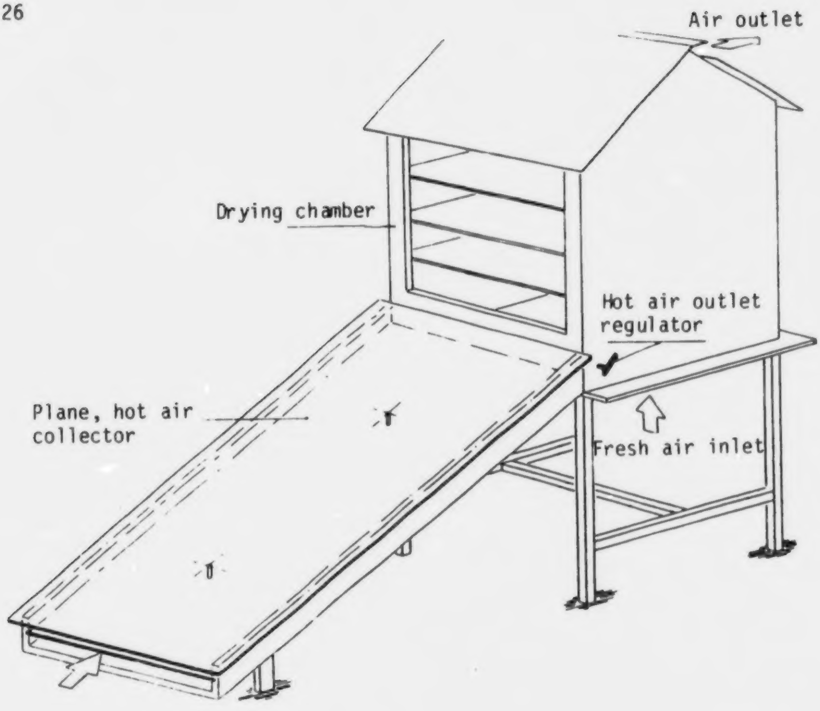


Fig. 3. Overall view of experimental dryer.

- Interior dimensions: width 970 mm, depth 750 mm, height 600 mm
- Exterior dimensions: width 1040 mm, depth 940 mm, height 600 mm
- Usable volume: 0.436 m^3
- Rack dimensions: 970 x 750 mm
- Number of racks: 4
- Drying surface: 2.0 m^2
- Surface to volume ratio: 6.67 m^2/m^3
- Materials: plywood and laths
- Rearloading double door
- Glass front face

Temperature and Relative Humidity of Air

Ambient temperature and relative humidity (RH) conditions were favourable for drying vegetable products between 15 November 1985 and 15 March 1986 (Fig. 4 is an example of 1 week, 26 November to 2 December 1985). The temperature varied from 22 to 24°C between 2200 and 0730 hours and from 45 to 50°C between 1000 and 1600 hours with peaks of 55-57°C.

Relative humidity and temperature inside the drying chamber follow a curve similar to that for ambient air; however, with a lag of about 30-45 minutes in the morning and about 60 minutes at the end of

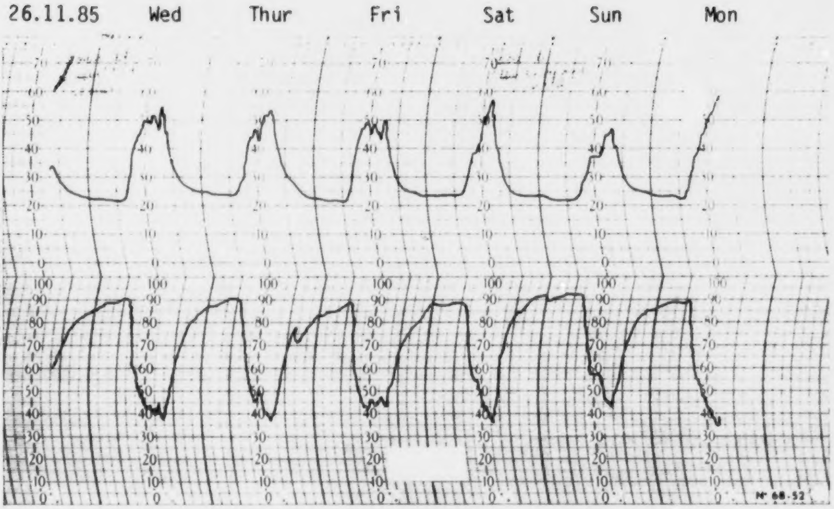


Fig. 4. Variation of ambient temperature (°C, upper trace) and relative humidity (%, lower trace).

the afternoon. This can be explained by the fact that, in the morning, the components of the dryer absorb heat in the process of attaining the air temperature and, at the end of the afternoon, the walls of the dryer, the racks, and the products have stored heat that, when released, delays the drop in air temperature.

Amaranthus hybridus Leaves

The leaves used were harvested between October 1985 and May 1986 from a field in a flooded valley near Yaoundé. These leaves were prepared less than 24 hours after harvesting.

The leaves were separated from their stems by hand, but the ribs were not separated from the leaves. They were then prepared according to the traditional recipe for *ndolé* used in the southern part of Cameroon for this type of vegetable.

The leaves, once separated from their stems, were cut with a knife, washed, and boiled for 10-30 minutes. The cooked leaves were then washed in cold water and squeezed dry by hand.

The product thus obtained was divided into three parts. The first part was used to study the drying speed under various conditions. The second part was dried to constant mass in an oven to determine the initial moisture content. The third part was dried in a solar dryer for use in taste and preservation tests.

The vegetables were dried in small balls of 0.5-1.5 cm diameter, and were spread out in a layer 1-4 cm thick in a solar dryer with a plane collector. The products were loaded on the trays at various densities: 4.0, 4.5, 5.0, 6.0, and 6.5 kg/m^2. The products were then dried to a moisture content of 8.75-9.00%.

The dried products were wrapped in plastic thermoseal bags and stored under ambient conditions (25-28°C) in an environment sheltered from light and humidity.

To test the reabsorption of water, the dry vegetables were exposed to moist air (90% RH) at 23°C for 48-72 hours. The gain in weight was from 8.6-17.0% of the initial weight of the vegetables.

We also conducted reconstitution tests. The prepared vegetables lose 88% of their mass by the end of drying. During rehydration, the dry products are immersed in boiling water for 30 minutes, then squeezed and weighed. Vegetables prepared in this way absorb about 2.25 times their weight of water. The rehydrated products thus have 337% of the initial mass of dry vegetables but only 40% of the mass of the vegetables before drying.

Dehydration of Vegetables

These vegetables, from the standpoint of their technical behaviour, are colloidal bodies with a capillaroporous structure. Such a structure facilitates the movement of moisture in the product during drying. Evaporation starts as soon as the partial pressure of the water vapour in the product (Pv) rises above that of the ambient atmosphere (Pa). Beyond a certain optimum cooking time, which is required to neutralize the fermenting agents of the vegetables, any continued cooking softens the vegetables, thereby imposing an additional constraint on the movement of water. The vegetables thus lose soluble substances and become rich in water content.

The traditional technology of preparation involves manual pressing of the boiled vegetables, either directly or with a jute bag. The manual press made at the École nationale supérieure polytechnique (ENSP) gives results that are essentially similar to those obtained with the traditional manual pressing process using a jute bag.

The initial humidity of the product is 400-650% of its dry mass, which is 18.6-20.0% of its initial mass. The variation depends on the process used in preparing the product, specifically the technique of preparing the vegetables, the duration of blanching the product, and the technique of pressing (pressure applied and its duration).

We selected a value of W^s = 467.55% as the average humidity for boiled vegetables relative to their dry mass, which corresponds to a moisture content of 82% relative to the initial mass of the sample.

Mass Exchange Characteristics During Dehydration of Vegetables

From the curve of evaporation rate as a function of time (Fig. 5), which is obtained in the process of drying a thin layer of product, two phases can be identified: first, the temperature adjustment phase, the period needed to equilibrate the vapour transfer from the product with the heat transfer to the product; and, second, the constant rate phase, whose characteristics are essentially typical of the water which accounts for the product's humidity.

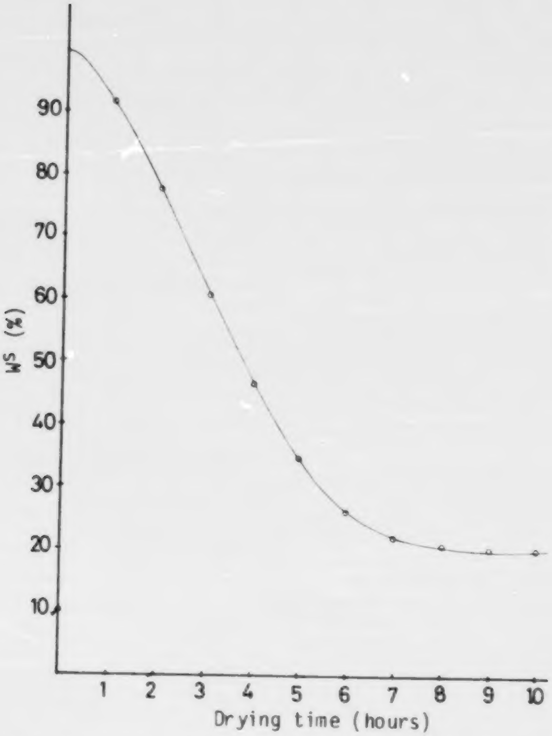


Fig. 5. Variation in moisture of the sample during drying.

Fournier (1979) has developed a schematic representation of the way that water is bound in the grain at 15°C (Fig. 6).

It may be strongly presumed that impregnation water was largely preponderant in the samples of vegetables prepared using the techniques studied. This impregnation water consists of the free water that is retained mechanically between the particles of the vegetables and between the walls of these particles, and the water that is bound by osmotic forces. The percentage of this water in relation to the total moisture content of the vegetables was not determined during this study.

Results and Discussion

The vegetables prepared using traditional methods and pressed by hand had a moisture content of 86% of their initial mass. For vegetables that were prepared in the same way but cut more coarsely (each leaf cut into four to six parts), the moisture content was 82% (Table 1). Increased cooking time does not improve the dry matter content, but rather reduces it.

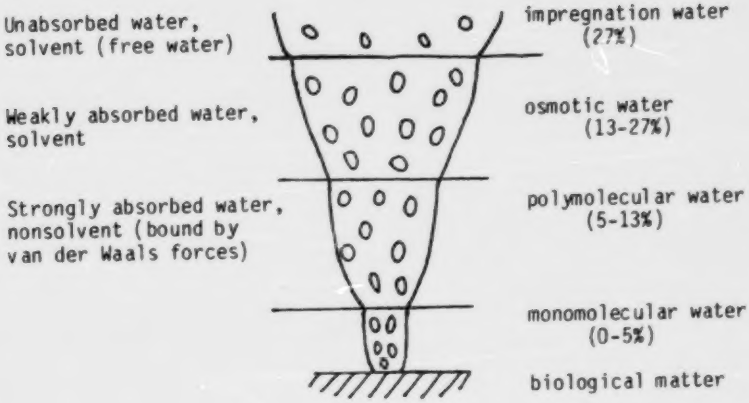

Unabsorbed water, solvent (free water)
impregnation water (27%)
Weakly absorbed water, solvent
osmotic water (13-27%)
Strongly absorbed water, nonsolvent (bound by van der Waals forces)
polymolecular water (5-13%)
monomolecular water (0-5%)
biological matter

Fig. 6. Schematic representation of bound water in grain (maize) at 15°C.

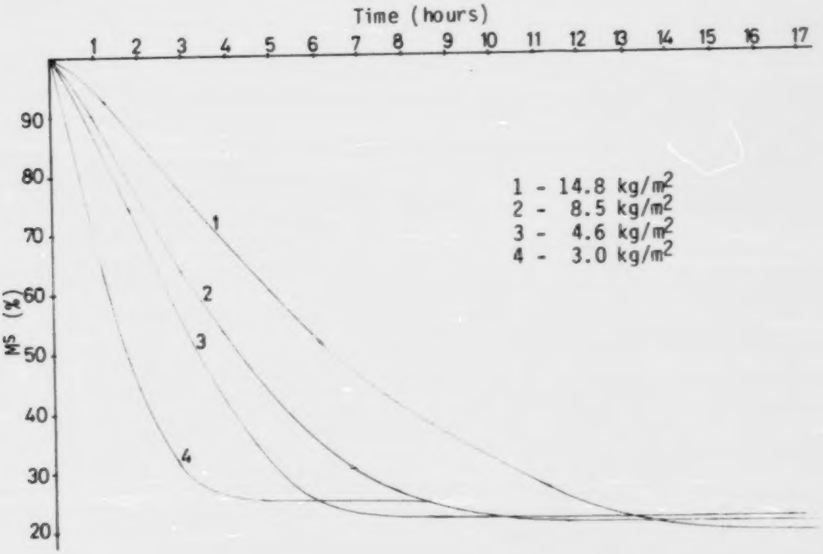


Fig. 7. Drying curves as a function of spreading density.

Because traditional cuisine requires that vegetables intended to accompany sauces should have precise dimensions, we studied a large sample of vegetables prepared using traditional methods to determine the distribution by size of particles of leaves in a mass ready to be added to sauces. We spread out the humid particles from a 2-g mass of

Table 1. Initial dry matter content of vegetables according to method of preparation.

Method of preparation	**Dry matter content (% of initial mass)**
Traditional preparation (finely cut, cooked for 30 minutes, pressed by hand)	14.38
Same preparation, but pressed with manual press	14.78
Same preparation and pressing, but cooked for 15 minutes	18.59
Coarsely cut, cooked for 15 minutes and pressed by hand	17.76
Whole leaves, cooked for 15 minutes and pressed by hand	19.94

Table 2. Distribution of particles of vegetable by size.

Area (mm^2)	**Dimensions (mm)**	**Number**	**% of total**
≥650	> 26 x 25	77	21.9
649-350	> 25 x 14	99	28.2
349-100	> 20 x 5	31	8.8
99-50	> 15 x 3.5	32	9.1
49-12.5	>7.5 x 1.5	49	14.0
<12.5	<7.5 x 1.5	63	18.0

Table 3. Drying times of vegetables according the size of largest particles.

	Mass of balls (g)			**Vegetables finely spread**	**Leaves prepared whole and finely spread**
	10	**5**	**2.5**		
Density (kg/m^2)	14.8	8.5	4.6	3.0	3.0
Time (hours)	16.7	14.7	10.0	4.0	6.0

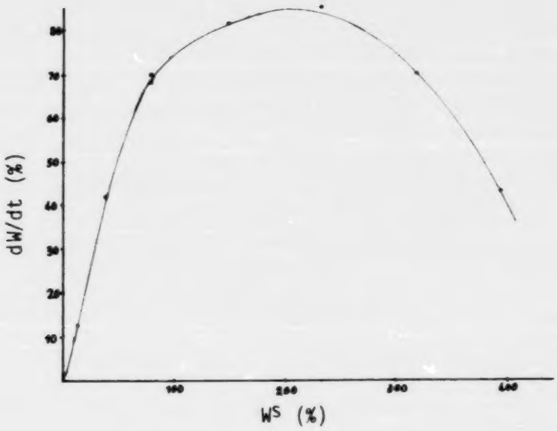


Fig. 8. Rate of water loss as a function of residual dry matter.

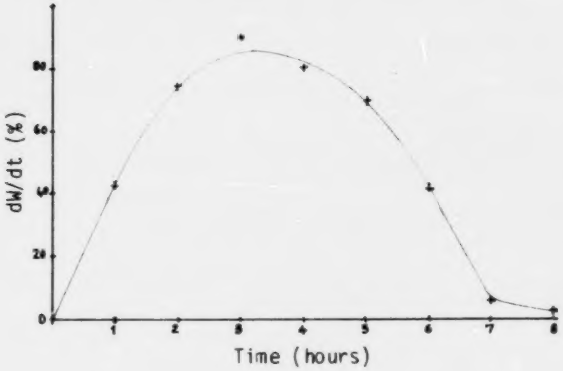


Fig. 9. Rate of water loss as a function of time.

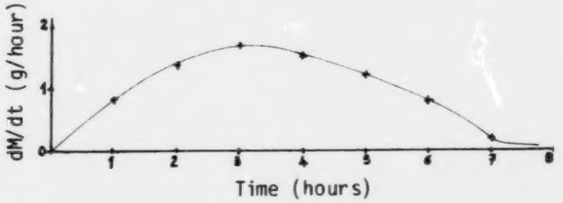


Fig. 10. Rate of mass loss as a function of time.

vegetables on a sheet graduated in millimetres. The outline of each particle before it is dried is easily determined because the humid particle is rich in chlorophyll.

In total, 351 particles of over 12.5 m^2 in area were counted. The largest particles, 22% of the total, had a surface area greater than or equal to 650 mm^2, whereas the smallest particles, 18% of the total, had an area less than 12.5 mm^2 (Table 2).

Comparative Tests on Vegetable Drying

Figure 7 shows drying curves for vegetables dried in layers of four densities: 14.8, 8.5, 4.6, and 3.0 kg/m^2. These correspond to vegetable balls of 10.0, 8.5, and 2.5 g and finely spread vegetables. The drying time to constant mass at a temperature of 48°C and 54% RH increased with increasing density (Table 3). The drying rate can also be expressed as rate of water loss as a function of residual dry matter (Fig. 8) or of time (Fig. 9) or as rate of mass loss as a function of time (Fig. 10).

Conclusions

Under conditions of indirect solar drying using natural convection, it would seem best to use low spreading densities for the products to facilitate air circulation. In the conditions prevalent in the region of Yaoundé, a drying cycle of only 1 day can be achieved if the leaves are cut coarsely and spread at a density of 3 kg/m^2, provided that the products are brought to the dryer at 0700 hours. The final moisture content of the dry vegetables is between 10.5 and 12.0%. Prolonged cooking of the vegetables to be dried does not seem to be justified.

Bibliography

Fournier, M. 1979. Paper presented at the Colloque sur la conservation des denrées alimentaires cultivées en climat chaud et humide, Yaoundé, 5-10 November 1979. L'Association des universités partiellement ou entièrement de langue française, Montreal, Canada.

Masseyeff. 1958. Industries agricoles et alimentaires en zones tropicales et sub-tropicales.

Tchiengue, E., Kaptouom, E. 1983. Le séchage des fruits, légumes et tubercules au Cameroun. Paper presented at the Conference of Experts on Developing Solar Drying Techniques in Africa, Rome.

OUTLOOK FOR SOLAR DRYING OF FISH IN THE GAMBIA

A.E. N'Jai[1]

Abstract *-- Three types of solar dryer -- tent, house, and dome shaped -- were tested for drying fermented fish in The Gambia. Although the dryers did not reduce drying time significantly, quality of the product in terms of reduced contamination by dirt and infestation by blowflies was improved. Other areas in the preparation of dried fish by the artisanal sectors that should be investigated are suggested.*

Introduction

To reduce postharvest losses in fish and fishery products, traditional processing technology is being improved in The Gambia. This includes improvements in fish smoking and drying and, for the latter, solar drying has been adopted using locally available, low-cost materials to build the solar dryers.

In 1983, the Fisheries Department of The Gambia (unpublished data) estimated the possible quantity of fish to be dried from artisanal landings in connection with a solar-drying project. Total artisanal landings were recorded as 8456 t, of which 1952 t were demersal fish. Of the 1952 t, all the cassava fish (Otolithus brachygnathus), sharks, and rays were presumably sun dried because these species are only used in this way. Of the balance of the demersal catch (1656 t), mainly groupers, croakers, grunts, and threadfins, it was estimated that at least 45-50% was sun dried. Landings of catfishes were recorded as 765.5 t and, because only small quantities of this species are smoked for local consumption, it is reasonable to estimate that about 70% was sun dried. Sea-snails are sun dried almost all year round but data on the amount are difficult to obtain.

Because substantial quantities of the total artisanal landings are sun dried, a technique that has several limitations and problems that lead to losses, the use of solar dryers was considered as an important step toward reducing losses during fish drying, especially during the rainy season. Although systematic quantification of losses has never been attempted, estimates from numerous observations suggest that losses are quite high and insect infestation prevalent. The problems of infestation are even more hazardous during the wet months. Thus, assuming that no matter how little the difference might be from traditional sun-drying, the use of solar dryers could play a vital role in fish-processing technology in the country (N'Jai 1985a).

---

[1] Fisheries Department, Banjul, The Gambia.

In 1983, with the assistance of the African Energy Programme of the Commonwealth Science Council (CSC), a solar drying project was launched by the Fisheries Department on a pilot scale. At the project's inception, a "solar-tent" design (Fig. 1) was adopted. This had been originally tested by Doe et al. (1977) but later modified and tested again by Trim and Curran (1983). Because both these studies generally postulated favourable results and because fish drying is a widely practiced traditional activity in The Gambia, the present project was initiated.

However, later in 1984, with the assistance of the Food and Agriculture Organization of the United Nations (FAO), a commercially manufactured dryer capable of holding 1 t of fish was tested. This dryer is dome shaped (Fig. 2) with frames made of metal hoops and has hooks for hanging fish while they dry (Fig. 3). Most recently, the design of the solar tent has been modified into a house shape (Fig. 4) and the dryer tested against the tent shape to determine any differences in efficiency and loading capacity.

This report summarizes the experiments conducted using the three designs and considers the effects of socioeconomic factors in technology transfer of this kind in developing countries such as The Gambia.

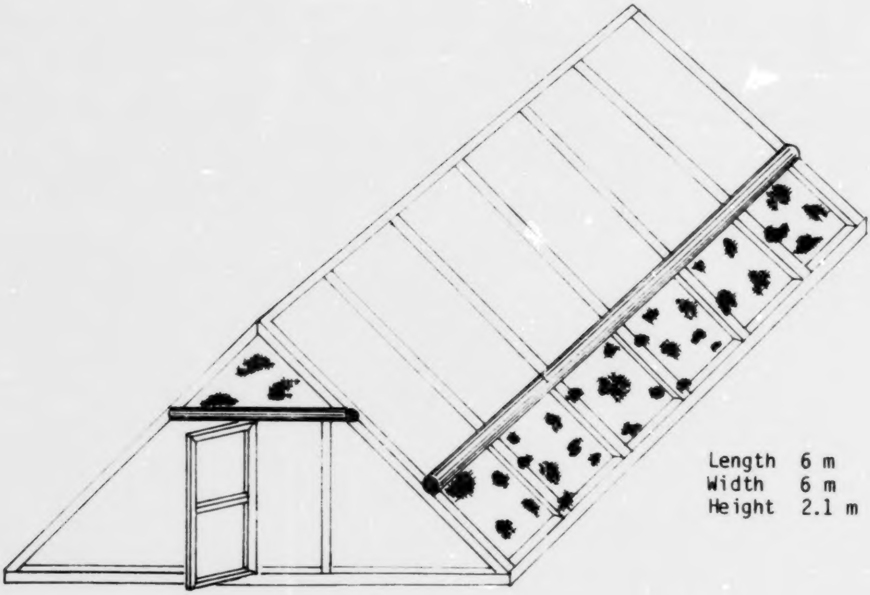


Fig. 1. Solar tent dryer.

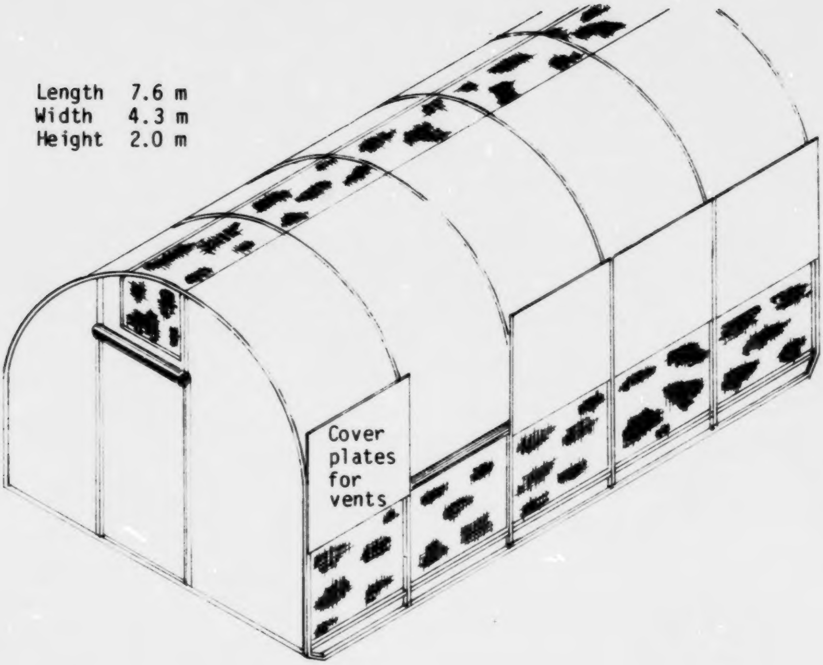


Fig. 2. Solar dome dryer.

Materials and Methods

Because of constraints related to artisanal landings and purchase of the catches, it was difficult to have the same species in all the batches. However, the following species were used: bonga (shads), croakers, threadfin, mackerel, and catfish.

Unfermented fish is unacceptable to the consumer in The Gambia, thus all trials of dried fish products were conducted with fermented fish. This was prepared by placing the fish samples in plastic buckets or concrete tanks covered with polyethylene and leaving them overnight. After fermentation, all fish samples were weighed (about 340 kg) and divided into two equal batches, one for solar drying and one for sun drying. Samples were then gutted, washed, and salted. Because the fish loses its rigidity after fermentation, they were at times difficult to handle during gutting and washing, and the fish flesh often disintegrated.

Batches were subsequently placed in the dryer under test or on wooden racks in the open. Temperature and humidity of the dryers and ambient were recorded before drying started and at intervals during drying. At the end of the drying period, the samples were reweighed and final moisture content determined using an Ohans 5100 HE Balance Moisture Meter.

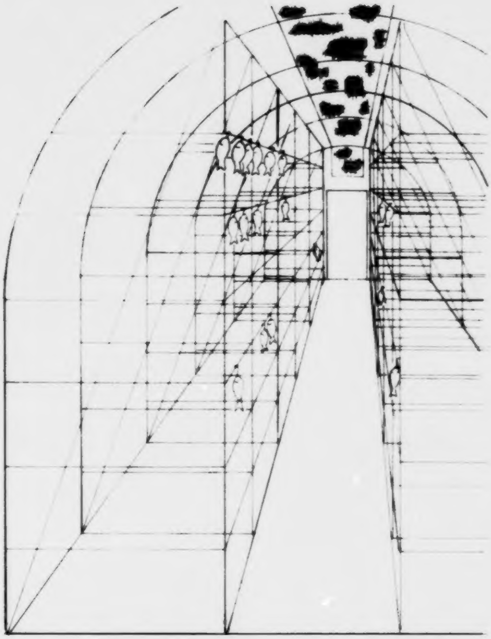


Fig. 3. Drying beams with hooks inside solar dome.

Because drying had to continue for several days, the air vents of dryers were shut and the fish on sun-drying wooden racks were covered with clear polyethylene each day before sunset.

Dryers

All the dryers operated by natural convection and were situated near the beach at artisanal fish-landing sites.

Solar Tent Dryer

As its name denotes, the tent dryer has a tent-shaped structure with frames made of rhun palm sticks, which are low-cost and available locally. Inside the dryer are two rectangular racks (Fig. 5) stretching along the sides of the dryer. On top of the racks, finely woven bamboo sticks (kirinting) are fitted firmly to carry the fish during drying.

The whole dryer is covered with clear polyethylene except at the base and the top of the end walls where air vents are provided. The vents at the base run the length of the dryer and, like those on the top, are fitted with fine-mesh plastic netting to prevent flies from entering the dryer. There is a door at one end of the dryer.

Inside the dryer beneath the racks are black metal plates that

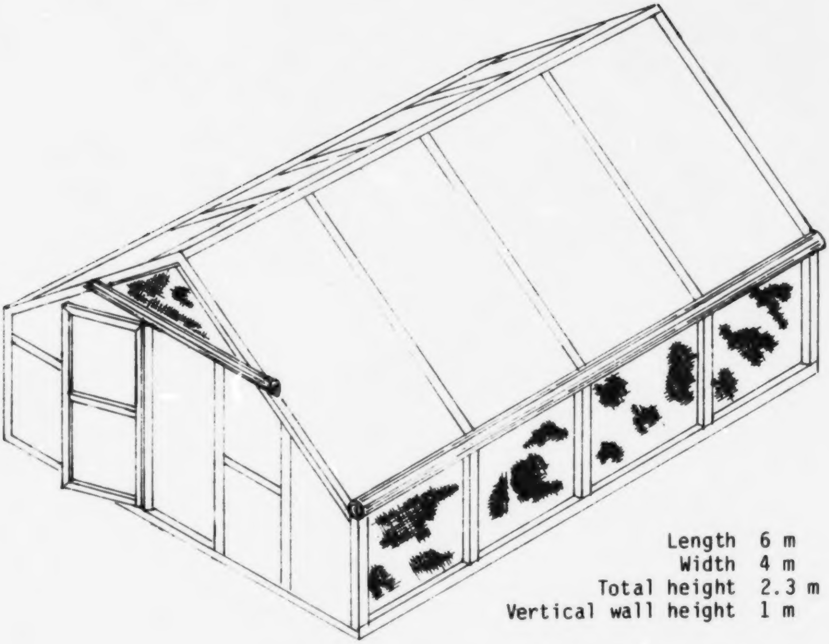


Fig. 4. Solar house dryer.

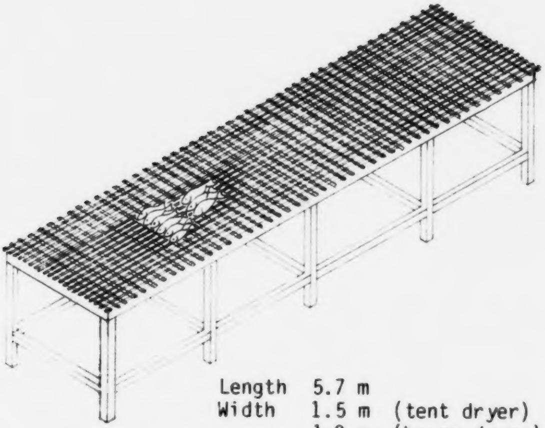
act as collectors of solar radiation. Dimensions of the dryer and racks are given in Figs 1 and 5. The side vents are 0.5 m high and 6.0 m long. The top vents are triangular in shape. The front one has an area of 0.7 m^2 and the back vent is somewhat smaller (the difference in the sizes was a construction problem and not a deliberate plan).

House-Shaped Solar Dryer

Like the tent dryer, the house-shaped dryer also has frames made of rhun palm sticks and is fitted with two drying racks beneath which are black metal plates. The structure is somewhat an adaptation of the tent-shaped design, but it is mounted on poles and beams 1 m off the ground to give it the shape of a house. Dimensions of the dryer and the drying racks are given in Figs 4 and 5. The side vents are 1 m wide and 6.0 m long and the top vents have an area of 0.5 m^2 each (front and back).

The dryer is clad with clear polyethylene (UV-resistant) and the vents are covered with plastic mesh to prevent entry of flies.

The loading capacity of both this dryer and the tent dryer is estimated at 400-500 kg, although during the trials enough fish was not available to load at full capacity.



Length 5.7 m
Width 1.5 m (tent dryer)
1.0 m (house dryer)
Height 0.8 m

Fig. 5. Drying rack inside solar tents.

Solar Dome Dryer

The solar dome dryer was manufactured in the U.K. by Clovis Lande and provided to the Department of Fisheries as an FAO grant-in-aid. It is basically for large-scale commercial use with a capacity of 1 t. Its dimensions are given in Fig. 2. Six metal hoops shaped as arches form the frame, which is covered with clear UV-resistant polyethylene. Inside the dome are vertical and horizontal beams: the latter allow for the fish to be hung on hooks while drying.

There are two doors, back and front, covered with a plastic material. There are vents along the bottom of the side walls and along the top at the centre of the arch. As in the other dryers, the vents are covered with plastic netting. The vents can be closed with metal plates that slot easily into special openings. This dryer does not use metal plate collectors; instead, the dryer is fixed to a black-painted concrete base.

Results

Differences in temperature and humidity between the tent and house dryer designs under loaded conditions were slight but both raised the temperature and lowered the relative humidity over the ambient values in January (Table 1) and May (Table 2). It is assumed that the differences in temperature and humidity between the dryers and the ambient would have been greater if the dryers had been located inland and not near the beach. In areas around the beaches, these parameters could be affected by weather conditions not necessarily the same as those inland. It is generally windy in these places and relative humidity is high.

Table 1. Comparison of temperature and humidity conditions under load in the solar tent and house dryers compared with ambient conditions for two trials, January 1986.

Date	Time of day (hour)	Tent dryer		House dryer		Ambient	
		Temperature (°C)	Humidity (%)	Temperature (°C)	Humidity (%)	Temperature (°C)	Humidity (%)
1st trial							
10.1.86	1345	33	17	38	21	31	29
	1545	38	30	37	22	34	22
11.1.86	1350	31	29	35	20	32	22
12.1.86	1100	27	24	25	27	23	24
	1400	34	24	37	9[a]	30	20
	1615	32	19	30	20	29	19
13.1.86	0950	23	29	21	26	19	36
	1330	32	23	29	27	26	28
	1445	31	24	29	18	26	23
14.1.86	0930	23	29	21	32	21	32
	1300	31	18	30	28	28	26
2nd trial							
17.1.86	1430	40	20	35	14	30	24
18.1.86	1330	30	24	29	26	26	28
19.1.86	0930	29	26	28	26	22	22
	1230	31	12	39	9[a]	26	-
	1600	35	12	32	14	31	12
20.1.86	1400	31	18	28	22	23	34
	1600	34	18	31	18	26	28
21.1.86	0915	20	31	19	22	19	28
	1230	30	24	28	22	26	32

[a] Questionable values.

Table 2. Comparison of temperatures and relative humidities in the solar dome dryer and under ambient conditions in two trials, May 1985.

Date	Time of day (hour)	Solar dome Temperature (°C)	Solar dome Humidity (%)	Ambient Temperature (°C)	Ambient Humidity (%)
1st trial					
17.5.85	1017	30.5	56	21.5	86
	1150	27.5	67	22.5	86
18.5.85	1219	24.0	70	23.0	77
19.5.85	1030	27.0	70	23.0	83
	1430	33.0	51	27.0	63
20.5.85	1121	31.0	54	24.0	76
2nd trial					
22.5.85	0910	29.5	62	25.0	76
	1450	27.5	72	25.0	76
23.5.85	1030	28.0	71	24.0	84
	1400	29.0	72	25.0	82
24.5.85	-	-	-	-	-
25.5.85	1145	29.5	51.5	26.5	68
	1410	31.5	66	27.5	74.5

Table 3. Final moisture content (%) of samples under three drying methods.

Species	Solar tent	Solar house	Traditional sun-drying racks
Bonga	62	61	65
Ladyfish	55	48	-[a]
Cassava fish	41	-	-
Threadfins	-	40	-
Mackerel	40	-	-

[a] Because of logistical constraints, moisture content of all the samples could not be determined after the drying period.

Overall efficiency of the dryers, in terms of reduced drying time, was not much greater than sun drying (Tables 3-5) but the difference, coupled with the importance of the dryers during the rains, was observed to be very essential in improving existing traditional technology.

Table 4. Weight of samples before and after drying in the solar tent and house compared with open-air drying (representative results from only one trial).

	Solar tent	Solar house	Sun-drying racks
Weight of samples (kg)			
At start	168.7	168.6	168.0
After 4 days of drying	93.8	94.6	118.9
% weight reduction	44.4	43.9	29.3

Table 5. Moisture content (%) of fish species after drying in two trials, May 1985.

Species	Solar dried	Sun dried
1st trial		
Ladyfish (Croaker)	39	39
Mackerel	38	42
Catfish	39	29
Threadfins (Cheken)	40	38
Ribbonfish (Pike congers)	40	52
2nd trial		
Cassava fish (Croaker)	36	15[a]
Mackerel	45	44
Catfish	40	40

[a] Small sliced pieces.

Discussion

The use of solar dryers for drying fish and other crops has wide applications in improving traditional food technology: especially in reducing postharvest losses, improving product quality and, in some cases, reducing drying time. The results presented here represent a series of trials and focus on the utility aspect of solar dryers to prevent losses and improve quality rather than on the physics of dryer operations and drying processes.

Although temperature and humidity were measured periodically during the experiments, the intent was not necessarily to compute "pick-up" efficiency, solar radiation, and other mechanical parameters, but to determine if there are vast differences in utilization between the dryers and ambient conditions and between the various dryer types.

Solar Dome

Trials during the study of the solar dome indicated a not too significant difference between solar and sun drying in terms of final moisture content (Table 5), weight reduction, and drying rates (N'Jai 1985). In fact, in previous experiments (Curran 1984) "very similar drying rates were obtained for sun and solar drying of several different products and blowfly infestation could be a problem." During the rainy season, however, many factors contribute to the abundance of blowflies; these cause hazards for fish drying and make infestation difficult to prevent. Walker and Wood (1985) have noted that "little is known about the actual mechanisms of blowfly infestation and the problem is widespread during sun drying under adverse conditions and is one of the greatest causes of losses in cured fish in Africa."

Temperatures that were recorded inside the dome, although of varying degrees at different times of the day and from one day to another, were not high enough to be lethal to flies entering the dryer. Doe (1979) reported that temperatures of over 60°C are lethal to blowflies but such temperatures may also have adverse effects on the nutritional quality of the fish (FAO 1981).

At times, the weather was rather hazy with plenty of wind and occasional cloud cover. This prevented high solar insolation and, hence, caused the low temperatures inside the dryer. Also, the covers for the vents and doors were not properly fitted making it difficult to regulate airflow inside the dryer. The dryer may be overventilated and this could partly explain its poor performance. No obvious disparity in drying time was found between solar and sun drying and the sun-dried products were ready at the same time as the solar-dried products. However, quality of solar-dried products was better in appearance and they contained fewer maggots than the sun-dried products.

Another reason for the poor performance of the dryer was its collector. This was the black-painted concrete slab and concrete has a comparatively low absorptivity value compared with metal plates. Thus, the rate at which the concrete floor can absorb solar radiation is so low that the temperature rise inside the dryer was slow. This being so, it was then assumed that the air flowing into the dryer and coming in contact with the floor (collector) would have a correspondingly low pick-up efficiency (N'Jai 1985b). The use of more suitable solar collectors, such as black-painted metal plates or black polyvinyl chloride (PVC), has demonstrated elsewhere more encouraging results in reducing drying time and lowering final moisture content of products (Doe et al. 1977; Doe 1979).

Thus, if the excess ventilation were reduced and the solar-collector surface improved, the solar dome could be an excellent dryer for large-scale commercial fish drying in the artisanal sector. Its loading capacity of 1 t is quite reasonable and, like the other dryers, it is very useful during the rains. One important disadvantage of the dome dryer is that it uses hooks to support the fish. This mainly limits drying to small pelagics or "cuts" of large pieces of fish flesh. Large, whole individual fish cannot be dried because they fall off the hooks easily.

Solar Tent and Solar House

As stated earlier, marked differences in temperature and humidity between the dryers and ambient conditions were not observed. During the course of trials, however, there was not enough sun and it was windy most of the time. This was the cool season (January) with generally low ambient temperatures and considerable cloud cover.

Nonetheless, on the basis of percent weight reduction during the drying periods, the solar-dried products of both dryers had better storage potentials (higher weight loss) and, hence, they would encounter a lesser degree of losses to beetles than products dried in the open.

The solar house is an adaptation of the tent design and was only constructed in an attempt to scale-up the structure for increased loading capacity. Although enough fish was not available to fill up both dryers simultaneously, practical observations during the trials have shown the capacity of the house dryer was not increased significantly; however, working in the house shape is more convenient.

General Discussion

Solar dryers are essential in the improvement of traditional fish drying technology. Blowfly infestation, which normally occurs during the initial stages of drying when the fish is wet, is considerably reduced with the use of solar dryers. Thus, where the purpose is to reduce postharvest losses, especially by preventing growth and proliferation of maggots in fish, the introduction of solar dryers need not necessarily be confined to tests of efficiency in increasing drying rates. Solar dryers can produce well-dried, dust-free products and can be used effectively during the rains when flies are abundant and traditional sun drying difficult. Even though it is virtually impossible under normal weather conditions to completely eliminate contact between fish and flies, this phenomenon could be considerably alleviated if solar dryers are used.

The technoeconomic aspect of solar drying of fish, although it has not been assessed adequately, has been favourable because the dryers are cheap and can be constructed easily. The cost of building the solar tents is about GMD 500 (1 U.S. dollar [USD] = 0.1302 Gambian dalasi [GMD]) and it takes only 2 days, including transport to the sites, to construct a dryer. The solar dome is a manufactured dryer and very expensive, but the other dryers are affordable by local fishing communities either on an individual or collective basis. The only problem that must be solved is the supply of the special type of polyethylene, which is not sold locally. A further problem is that, given the prevailing consumer behaviour, the solar-dried products could not find better market prices than the traditional sun-dried products because appearance is of secondary importance to need among the consumers in the country.

The use of solar dryers has so far stimulated a genuine interest and involvement of nationals, and some entrepreneurs have expressed their desire to adopt the facility for large-scale fish drying. It was for this among other reasons that the tent design was scaled-up in an attempt to increase the loading capacity. The use of large-scale dryers can play a meaningful role in improving fish-drying and loss-reduction technology in The Gambia. During the rainy season when sun drying is difficult and there appears to be seasonal peak in abundance of certain species, the use of solar dryers will be found indispensable.

However, it has been noted that the introduction of any new technology to the traditional sector in developing countries is usually met with problems and constraints that are fundamentally socioeconomic. For instance, traditional fish processors engaged in drying are commonly obsessed with the weight of their products and, thus, prefer dried fish with some moisture, enough to give a greater weight, and therefore more money, when marketed on a wholesale basis.

Furthermore, solar dryers should not be introduced in isolation from other parameters that effectively contribute to losses and also need improving. Because fermenting is a stage in the traditional process that should not be omitted if the products are for local consumption, this aspect needs investigating for improvement. Better salting methods and storage and packaging are all areas that should be studied with a view to improving them so as to complement the improvement made in the drying technology (N'Jai 1985a).

Taking into account the general view of local processors who rely on sun drying, investing in this new technology might seem folly because, even with a well-dried and cleaner product, the price remains the same or almost the same as that prepared traditionally. Therefore, local processors must be shown how solar drying can reduce losses and thus increase the weight of the final product produced from a given input (N'Jai 1985a).

Undoubtedly, such actions would require intensive and effective operations of extension services, especially at the initial phase of introduction when both skepticism and enthusiasm are expressed by the target communities. In this direction also, close interactions between extension and research and development staff of the implementing institution would be imperative to identify and select appropriate strategies and approaches to use when introducing the technology.

Conclusion

In spite of all the technical problems and inadequacies associated with solar drying in terms of increasing drying rates and improving product quality, the use of low-cost, locally made dryers cannot be disputed as having important advantages in reducing postharvest loss in the traditional sector.

Solar dryers produce well-dried products with reasonably long storage life. When used, the degree of losses due to insect infestation and maggots becomes insignificant.

Solar dryers for fish, however, should not be introduced in isolation. Other parameters, which are integral aspects of the drying process and effectively contribute to losses, should be investigated and improved. For instance, better fermenting techniques, improved salting, better packaging and storage methods, and proper sanitary conditions are areas to be looked into and developed.

Acknowledgment -- I acknowledge the financial support of the Commonwealth Science Council and the British Overseas Development Administration.

References

Curran, C.A. 1984. Report on a visit to The Gambia to investigate the reduction of losses in traditionally dried fisheries products. Tropical Development and Research Institute, London, U.K. Report R1222 (L), 55 pp.

Doe, P.E. 1979. The polythene tent fish drier: a progress report. Paper presented at the International Conference of Agricultural Engineering in National Development, held at the Universiti Pertanian Malaysia, Serdang, Selangor, September 1979. Paper 79-12.

Doe, P.E., et al. 1977. A polythene tent drier for improved sun-drying of fish. Food Technology in Australia, 29(11), 437-441.

FAO (Food and Agriculture Organization of the United Nations). 1981. The prevention of losses in cured fish. FAO, Rome, Italy. Fisheries Technical Paper 219.

N'Jai, A.E. 1985a. Fermenting and drying fish in The Gambia (considerations and possible impact of commercial solar drying in the artisanal fisheries sector). FAO, Rome, Italy. Fisheries Report 329, Supplement FIIU R329.

____________ 1985b. Trials of a solar dome for fish drying. Fisheries Department, Banjul, The Gambia. Publication 39.

Trim, D.S., Curran, C.A. 1983. A comparative study of solar and sun drying of fish in Ecuador. Tropical Development and Research Institute, London, U.K. Report L 60, 44 pp.

Walker, D.I., Wood, C.D. 1985. Non-insecticidal methods of reducing losses caused by infestation of blowflies (Diptera) during fish curing procedures. FAO, Rome, Italy. Fisheries Report 329, Supplement FIIU R329.

CIRCULATION OF AIR IN NATURAL-CONVECTION SOLAR DRYERS

Herick Othieno[1]

Abstract *-- Because the drying rate of any product depends on the relative humidity of the air used for drying, a good solar dryer must significantly reduce the relative humidity of the air and at the same time produce a high airflow. Natural-convection solar dryers can significantly reduce the relative humidity of air through heating, but many of them cannot achieve high airflow. Low flow rate in these devices has been the main cause of their failure. This paper presents the analysis of buoyancy-induced flow in such dryers and suggests a method of enhancing the airflow. The experimental analysis has indicated that airflow can be enhanced by a carefully designed chimney. However, the buoyancy-induced pressure, which creates the airflow, must be of the same order of magnitude as the pressure drop across the product to be dried.*

Introduction

In Kenya, over 80% of the total population live in rural areas where agriculture is the main occupation. Often the people suffer from food shortages: some caused by natural disasters, others by excessive postharvest losses because of poor storage facilities. To improve food security, farmers must use better techniques of food production, processing, storage, and distribution. This will enable the people to have food even during dry seasons.

One method of preserving foodstuffs in the tropics is to dry it to a very low moisture content before storage. Traditionally, farmers have allowed the crops to dry in the field before harvesting. This method is becoming increasingly unpopular, however, as the demand on the land increases with increased population. Furthermore, Harris and Lindblad (1978) have shown that field losses begin to occur immediately as the crop matures and they can rise to as much as 25% in the humid tropics. Therefore, mature crops should not be left in the field for too long. In areas of high potential yield, farmers plant and harvest twice each year and, therefore, must harvest the crop as soon as it matures to allow the new crop to be planted. The harvested crop is either sold immediately or dried and stored for future use. Lack of drying and storage facilities at the farm may be a problem; therefore, adequate low-cost drying and storage facilities are needed.

---

[1] Appropriate Technology Centre, Kenyatta University, Nairobi, Kenya.

In Kenya, the government has embarked on programs of improving large-scale storage facilities at the major government stores. However, this effort may not improve the situation noticeably if nothing is done at the farm level. Therefore, several research workers and rural development agencies are directing their attention to the problems of individual small-scale farmers. As a result, various types of solar crop dryers and improved on-farm grain stores are being introduced to the farmers by various organizations and institutions.

The work reported here is one of the attempts to ensure that the crops delivered to the government stores and those stored on the farm are adequately dried for long-term storage. Various designs of solar crop dryers have been field tested and one (a combined direct-indirect solar dryer operating with natural convection) has been shown to be a technical success. However, most of the farmers for whom it was designed are not yet willing to spend money to acquire it even though it has many advantages over the traditional open-air sun-drying.

Types of Dryers

Many research workers are now engaged in solar crop-drying projects in Kenya. However, one of their major constraints is that electricity and other forms of conventional energy are not readily available to the intended users of the dryers. Thus, the dryers must be designed to operate without an external energy source, that is, they should operate on some natural phenomenon. Most types of dryers that have been considered in Kenya operate by natural convection, which is less expensive, but also less efficient, than forced convection.

The simplest of these dryers is a tray covered with clear polyethylene to allow solar radiation to reach the wet product. The tray can be permanently built on the ground using pressed bricks or concrete blocks, or it can be made portable by constructing it out of wood or metal sheets.

The principle of operation of this dryer is simple: solar radiation enters through the top transparent cover and is absorbed by the collector that then heats the air inside the chamber. The heated air becomes less dense than the ambient air and therefore escapes from the chamber through the outlet holes on the sides of the cabinet (Fig. 1). This creates low pressure and ambient air is drawn into the chamber through inlet holes along the lower side of the cabinet just below the tray. A continuous flow of air through the dryer is thus established.

The air passing through the wet product is at ambient temperature and, therefore, does not heat the product. Its role is to pick up the moisture removed from the product through direct heating. Generally, the airflow through the product is very low and, therefore, the air above the tray is usually saturated. This causes condensation of water vapour on the inside surface of the transparent polyethylene cover. This process, which naturally reduces the amount of solar flux transmitted into the chamber, has been observed experimentally and occurs despite the ventilation. McDowell (1973) improved this type of dryer, designed for a variety of tropical crops, considerably. Some foodstuffs deteriorate by losing vitamins and nutrients when dried in

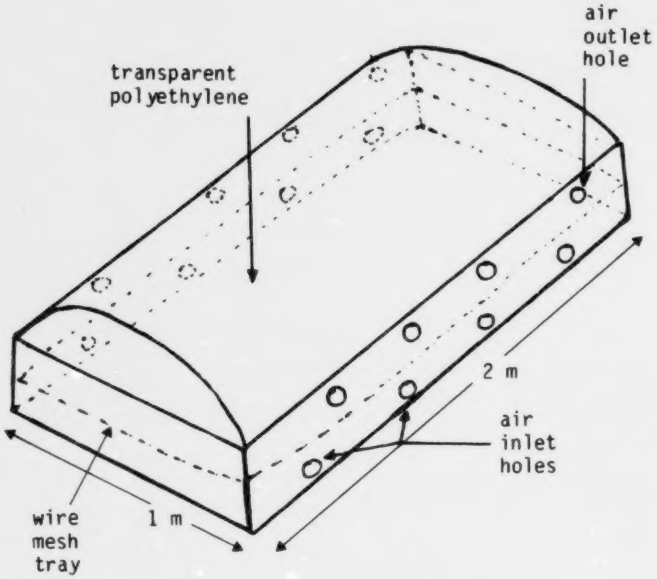


Fig. 1. Direct solar cabinet dryer (tray type).

direct sunlight. Therefore, the first improvement was made by introducing a black cover under the clear cover to shade the product from direct sunlight. The other improvement was an attempt to store heat, by using blackened stones at the bottom of the dryer, and so to increase the drying time. These improvements did not significantly improve the drying efficiency of the dryer: the mass flow of air still remained low.

In Kenya, Wright and Waddle (n.d.), working at Egerton College of Agriculture in the late 1970s, further modified the cabinet dryer with the aim of avoiding bleaching of the vegetables and increasing its efficiency. The rectangular-shaped cabinet was divided into two chambers: an air heating chamber and a drying chamber. Clear polyethylene plastic was placed over the heating chamber to allow solar radiation to heat the air. Black polyethylene was also placed under the chamber to absorb the heat and to keep out moisture from the ground. Another black polyethylene sheet was also placed over the drying chamber to prevent bleaching. Ventilation holes were not provided along the sides but an opening in the front of the unit allowed ambient air to enter the heating chamber and another opening at the rear of the drying chamber allowed moist air to escape from the unit (Fig. 2). Thus, sunlight passing through the clear polyethylene into the chamber heats the air, which then flows by natural convection through to the drying chamber, where it picks up moisture as it passes through the product, and then escapes through the opening at the rear of the unit. This dryer could also be used as a direct dryer for crops that are not subject to bleaching if the product is placed directly into the heating chamber. In both systems, the airflow is very low and,

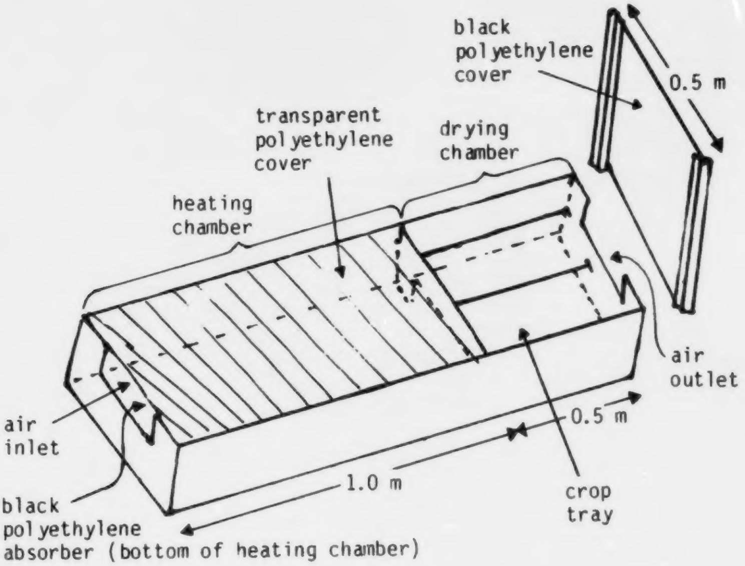

black polyethylene cover
0.5 m
transparent polyethylene cover
drying chamber
heating chamber
air outlet
air inlet
0.5 m
1.0 m
crop tray
black polyethylene absorber (bottom of heating chamber)

Fig. 2. Portable indirect solar dryer.

again, the improvements did not significantly improve the performance of the dryer.

As trials to improve the performance of natural-convection dryers continued, Othieno et al. (1981), following the success of a solar rice dryer investigated by Excell (1980), designed an indirect solar crop dryer with a chimney and proper orientation to enhance convective airflow through the unit. The dryer was studied, both theoretically and experimentally, and field-tested in Kenya. The overall program was to design small-scale, natural convection, solar crop dryers with particular application in Kenya to dry shelled maize from about 20% down to 13% moisture content (wet basis). The dryer (Fig. 3) was an indirect type consisting of an air heater, an opaque crop bin, and a chimney. The heater, made of a glass cover and black absorber plate, was inclined at an angle of about 20° to the horizontal to allow the heated air to rise up the unit with little resistance. Collectors that are inclined too steeply in the tropics do not receive adequate solar energy to heat the air to the required temperature. Therefore, chimneys must be used with natural convection dryers. Additional energy at the base of the chimney greatly enhances the operation of the dryer by increasing the airflow through the grain stack. Inside the opaque drying bin was a tray, made of fine wire mesh, to hold about 100 kg of maize. Above the bin was a chimney to enhance the airflow upwards.

Sunlight passes through the transparent glass cover and heats the chamber, which in turn heats the air. Heated air then rises up the unit by natural convection into the crop bin. As air passes through

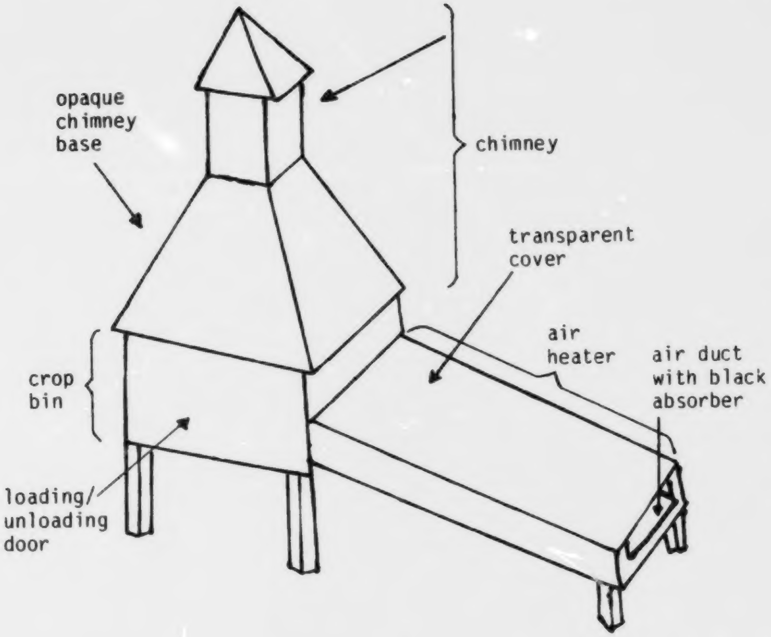


Fig. 3. Indirect natural convection solar dryer.

the crop stack in the tray, it picks up moisture from the crop and flows out through the chimney.

The flow of air in this dryer is much better than that of the horizontal cabinet dryer. However, drying does not occur uniformly: the bottom layer of grain dries very rapidly while the top layer remains wet for a long time. This occurs because the airflow through the grain stack is not sufficiently high. Thus, by the time the warm air gets to the top layer of grain, it is already saturated with moisture and cannot pick up any more. Two methods of dealing with this situation have been suggested: to stir the crop manually at least twice each day or to heat the air above the grain stack.

The first approach requires someone to stay nearby to stir the grain. This is not attractive because one of the objectives of the dryer is to eliminate the labour that is normally required when the traditional method of open-air sun drying is used. Furthermore, opening the unit to stir the grain causes a sudden loss of heat that temporarily lowers the drying rate.

Thus, the second option was chosen (Othieno 1986). The base of the chimney was modified to allow solar energy to heat the grain from the top. The east- and west-facing sides of the chimney base were made of glass windows so that direct sunlight could heat the top of the grain stack. This modification converted the indirect dryer into the combined indirect-direct type. However, it can only be used to dry crops that are not subject to bleaching or any other form of deterioration due to direct sunlight. If black-painted plates are placed behind each window, the windows also become solar collectors and the whole system becomes an improved indirect solar dryer. This latest design is structurally the same as Fig. 3, but is more efficient than the first designs reported by Grainger et al. (1981) and Othieno et al. (1981).

In 1985, the Department of Food Science and Technology at the College of Agriculture and Veterinary Science, University of Nairobi, imported a small-scale solar crop dryer from Switzerland. This dryer is an indirect type and operates by a mixture of natural convection and forced convection. At the top of the chimney is a wind-operated fan that draws air upwards through the dryer. During very bad weather, the air can be heated by a gas burner fitted at the bottom of a second air inlet manifold (Fig. 4). Inside the drying bin are four trays with wire mesh bases to allow air to pass through the vegetables. The trays are each about 0.5 m wide x 0.75 m long x 0.05 m deep. Thus, in terms of loading capacity, it is similar to the dryer

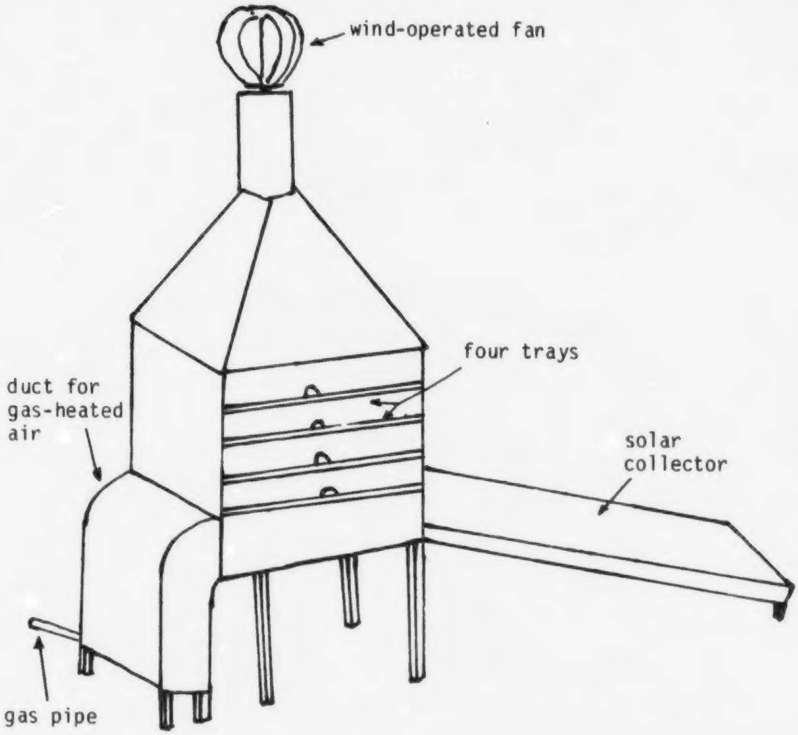


Fig. 4. Solar vegetable dryer with auxilliary gas heater (capacity of 85 kg on four trays).

in Fig. 3. The performance of this dryer is yet to be compared with that of the latest design by Othieno (1986).

Performance Comparison of the Dryers

The performance of the indirect natural-convection solar dryer (Fig. 3) was compared with that of the improved dryer having two additional collectors at the chimney base. The two dryers were structurally the same and equal in size. The dimensions of the dryers were:

- Collector -- 1 m wide x 2 m long x 0.05 m deep (gap between glass cover and black painted absorber plate). The absorber was a matt black painted plywood, which is cheap and readily available in Kenya.
- Crop bin -- inside cross-section of 1 x 1 m; contains two wire mesh trays each 0.05 m deep; inside walls made of plywood.
- Chimney -- cross-section of 0.2 x 0.2 x 0.5 m high; chimney base and sides pitched at an angle of 45°.

The total height of the dryer from the ground to the top of the chimney was 2 m, which was made up of the chimney assembly, crop bin (0.4 m deep), and support legs (0.6 m high). Apart from the chimney assembly, the crop bins and the collectors were insulated to reduce heat losses by conduction. The two collectors were both inclined at an angle of 15° to the horizontal.

The two dryers, each loaded with a thoroughly mixed load of maize (100 kg) having initial moisture content of 19% (wet basis), were placed 3 m apart to avoid any shadowing effect. Each tray had 50 kg of maize with a depth of 0.05 m making a total grain depth of 0.1 m for each dryer. Moisture contents of the grain from each tray in the dryers were simultaneously measured at equal intervals using Marconi Moisture meter (type TF 933C). The output air temperature from each collector and the temperature of air inside the chimney base were also simultaneously recorded using SWG 40 copper/constantan thermocouples connected to a multichannel Solartron Data Logger (type 3430B).

It was assumed that the solar radiation flux at the locations of the dryers would be the same. Three comparison runs were made during November 1985 when the days were generally sunny and cloudless. The results indicated that the improved indirect solar dryer with additional collectors at the chimney base was consistently more efficient than the standard indirect dryer. Typical examples of the measurements are shown in Figs 5 and 6). The mass flow rates of air through the dryers were also compared (Fig. 7) and it was confirmed that the heating of the air at the base of the chimney enhances airflow and so improves the drying efficiency. This fact is also reflected in the differences in the output air temperatures from the two collectors; higher airflow will result in lower collector output air temperature and faster drying rate. The airflow measurements were taken inside the chimneys using a Prosser Air Velocity meter (type AVM 502) and are reported directly (in m/sec) because the cross section of the two chimneys were the same.

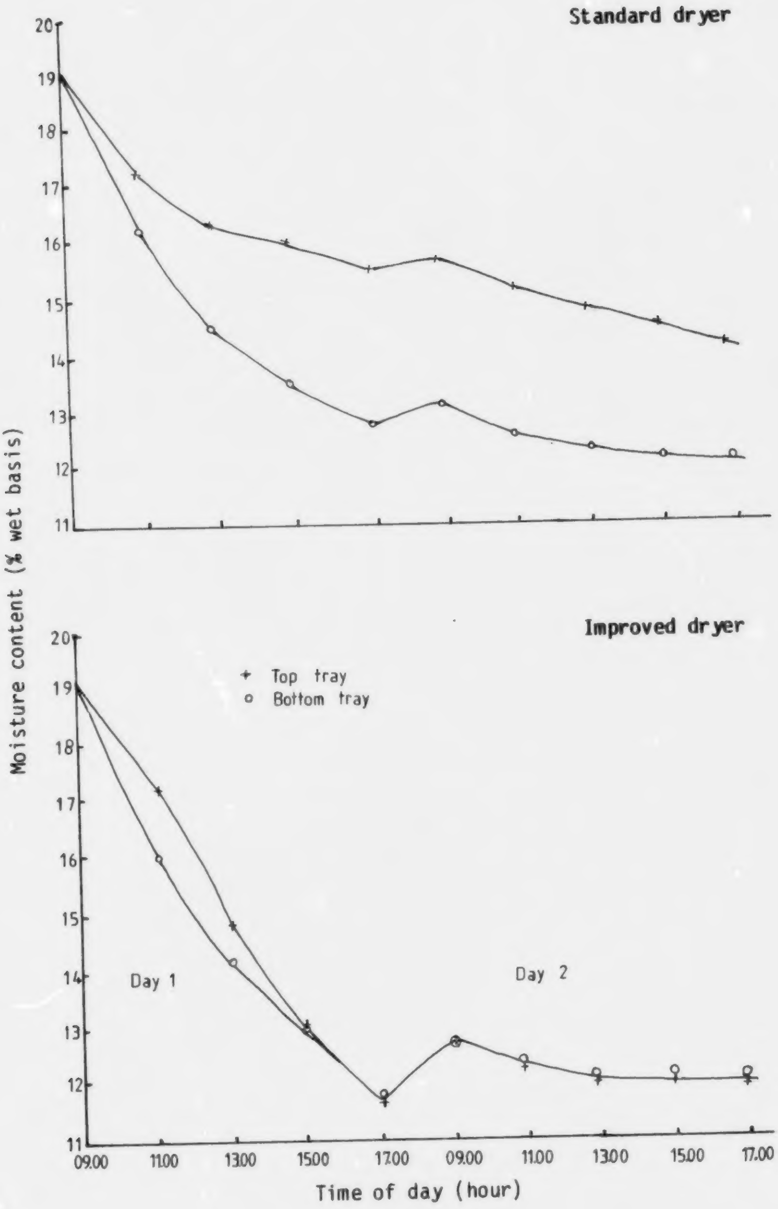


Fig. 5. Drying pattern of maize using a standard indirect solar dryer and one improved with additional collectors at the chimney base. The grain was not stirred or removed from the dryer during the whole process.

Air Circulation in Natural-Convection Dryers

Several factors play an important role in the drying process. Among the most important are airflow, available surface area, air temperature and humidity, and the moisture content and porosity of the product to be dried. Apart from the moisture content and the type of product to be dried, simple solar dryers can influence the other

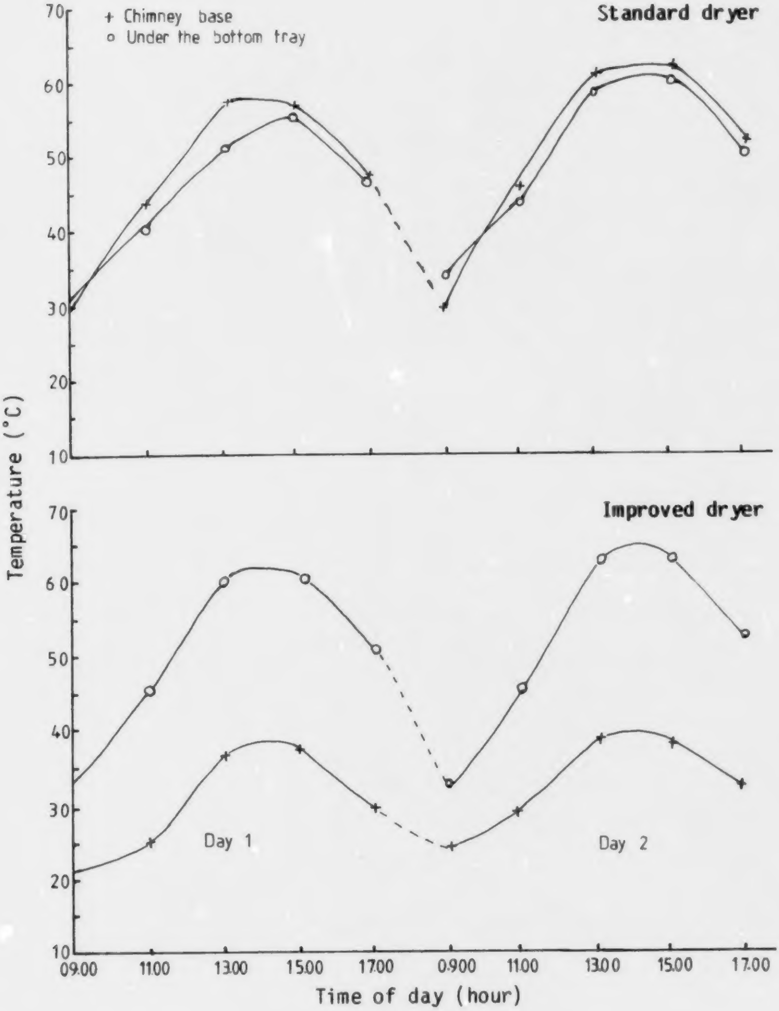


Fig. 6. Temperatures of air in a standard indirect solar dryer and one improved with additional collectors at the chimney base.

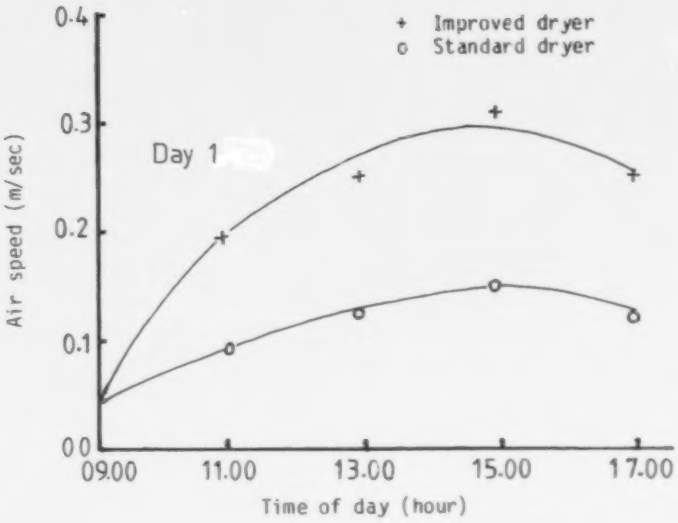


Fig. 7. Air speed through the chimneys of the two dryers.

factors. That is, by heating the air, the right temperature and relative humidity can be achieved to effect the drying process.

The airflow, which perhaps is one of the most important factors, is not sufficiently high in natural-convection solar dryers. At present, this is one of their major shortcomings. Therefore, to design a "working" natural-convection solar dryer, it is very important to know which factors affect the buoyancy-induced air circulation through the dryer. Othieno (1985a) analyzed the buoyancy-induced airflow and the pressure head created above atmospheric pressure and found that the buoyancy-induced pressure that initiates the motion of air through the dryer is:

$$\Delta P = (\rho_0 - \bar{\rho}_a) g H \qquad [1]$$

where ρ_0 is the density of ambient air, $\bar{\rho}_a$ is the average density of air inside the air heater, g is gravitational acceleration, and H is the vertical height of the air heater.

As the air flows through the dryer, its pressure decreases due to wall friction and changes of direction inside the dryer. It was observed that the dynamic pressure due to the velocity of air is very small and could be neglected. The largest pressure drop in the system, which significantly affects the performance of the dryer, occurs inside the grain stack. The magnitude of this important pressure drop for different crops has been experimentally determined by many researchers and can be estimated from expression obtained from the data given by Shedd (1953):

$$\Delta P_x = K(U_g) d_g \qquad [2]$$

where d_g is the thickness of grain stack and $K(U_g)$ is the pressure drop per unit depth of grain and is dependent on air velocity, U_g. When U_g equals zero, the value of K must also be zero.

From equation 1, it is clear that natural-convection solar dryers must have a large head, H, if significant pressure difference is to be achieved by the heater. This requires that the heater should not only be inclined to the horizontal but it should also be long enough to have a large H. From this analysis, one should not expect horizontal or near-horizontal dryers without chimneys to perform well.

Discussion and Conclusion

These dryers have several advantages over the traditional method of spreading the product to dry in open sunlight. These advantages are now well known (Othieno 1985b) and the dryers are not too expensive. The 1986 Othieno design, which is considered to be expensive, costs about USD 250 but those built for the farmers could cost less. Therefore, one would expect the demand for these dryers to be high, especially with such serious seasonal food shortages in Kenya.

The situation, however, is different. Farmers are not willing to spend any money to acquire the dryers. This may be attributed to several factors such as underemployment (or unemployment) in the rural areas of developing countries and the fact that traditional sun-drying does not cost anything. Solar energy costs nothing and the land area for spreading the product is always available in the rural areas. The farmers, therefore, do not appreciate the advantages of the solar dryers.

The main reason for drying is to reduce water content (moisture content) so that the foodstuff can be stored for future use without the need for refrigeration because, as is well known, dry food can be stored safely for long periods. For this reason, the Kenyan government has spent a great deal of money to import large-scale oil-fired dryers to dry agricultural products for export or home consumption. Some of these dryers are operated at the depots of the National Cereal and Produce Board. (One such depot spends about USD 3000 on oil to operate the dryer during the drying period.) If all the cereals received from the farmers by the Board had been dried down to the required moisture content (i.e., less than 13.5% moisture content, wet basis), the government would save its much-needed foreign earnings. However, the individual farmer does not realize this, and it is time that governments of developing countries assisted not only by educating the farmers but also by supporting researchers to disseminate new technical developments. Obviously, natural-convection solar dryers are already a technical success in that they are capable of raising air temperatures and consequently reducing relative humidity to increase the drying rates. In addition, these high temperatures are a deterrent to insect penetration and growth of fungi: the final dried product is, therefore, of a higher quality. Why then are these dryers not readily accepted by the farmers as necessary farm devices?

Because dryers are used only intermittently, their purchase is not particularly attractive to the farmers. Also, because of their size, most of these dryers have limited other applications and drying is only done during a short period of the year. It is, therefore, recommended that multipurpose solar dryers be designed and tested. Some of these should be able to serve as food stores when there is nothing to dry. Lack of demand for the existing dryers may also be associated with the fact that most researchers tend to ignore the contribution of the end user during the research and development stages. Furthermore, many researchers in developing countries tend to work in isolation, ignoring the role of other scientists, such as food scientists and nutritionists in this case. For this technology to succeed, it must be developed by a joint effort of a multidisciplinary team and the needs of the farmers must be properly considered.

Acknowledgment -- The author acknowledges the financial support of the Commonwealth Science Council and the British Overseas Development Administration.

References

Excell, R.H.B. 1980. A simple solar rice dryer: basic design theory. Sunworld, 4(6), 186-190.

Grainger, W., Othieno, H., Twidell, J.W. 1981. Small scale solar crop dryer for tropical village use -- theory and practical experience. In Hall, D.O., Morton, J., ed., Solar technologies in the eighties (Vol. 2): proceedings of the International Solar Energy Society's Solar World Forum, Brighton. Pergamon Press, Oxford, U.K. pp. 989-996.

Harris, K.L., Lindblad, C.J. 1978. Postharvest grain loss assessment methods. American Association of Cereal Chemists, St Paul, MN, USA.

McDowell, J. 1973. Solar drying of crops and foods in humid tropical climates. Caribbean Food and Nutrition Institute, Kingston, Jamaica. Report CFNI-T-7-73.

Othieno, H. 1985a. Design factors of small scale thermosyphon solar crop dryers. In Awe, O., ed., Proceedings of African Union of Physics Conference. Ibadan, Nigeria. pp. 135-143.

———— 1985b. Optimisation of solar air heating collectors used for crop drying. In Renewable energy developments in Africa: proceedings of the International Conference on Research and Development of Renewable Energy Technologies in Africa, Mauritius, 25 March - 1 April 1985 (Vol. 2). Commonwealth Science Council, London, U.K.

———— 1986. A comparative study of natural circulation solar maize dryers in Kenya. In Proceedings of the International Conference on Energy, Food Production and Postharvest Technology, Nairobi, Kenya.

Othieno, H., Grainger, W., Twidell, J.W. 1981. Application of small scale solar crop dryers to maize drying in Kenya. In Twidell, J.W., ed., Energy for Rural and Island Communities (Vol. II). Pergamon Press, Oxford, U.K. pp. 377-386.

Shedd, C.K. 1953. Resistance of grains and seeds to air flow. Agricultural Engineering, 34, 616-619.

Wright, C.A., Waddle, D. n.d. [1970s]. A portable indirect solar dryer. Report for The South-East Consortium for International Development, Egerton College. Nakuru Press, Nairobi, Kenya. pp. 1-18.

SOLAR ENERGY RESEARCH FOR CROP DRYING IN KENYA

F.B. Sebbowa[1]

Abstract — *Some of Kenya's crops that, in general, can be dried in solar energy dryers are outlined. Using the design and test procedure for a pyrethrum solar crop dryer as an example, the sort of insolation data available, other pertinent design data required, and likely performance in a large, major agricultural area of Kenya are indicated. In particular, this design indicates that, for the rainy season (about 30% of the pyrethrum crop-year), an auxilliary energy source is required for those crops that are harvested during the rains and need prompt drying to prevent quality deterioration. This paper gives the design modifications to accommodate this auxilliary energy supply. Also some of the major socioeconomic obstacles that are likely to hinder the popularization of this particular dryer to its intended end users are discussed. Finally, some of the general techno-socioeconomic impediments to faster progress in solar crop dryer research, such as poor research methodology and defective technology exchange, which are pertinent to Kenya in particular and Africa in general, are outlined.*

Some of Kenya's Agricultural Drying Requirements

Kenya is situated between latitudes 3°S and 4°N and longitudes 35°E and 41°E. Its altitude ranges from sea level in its southeastern corner to 3000 m above sea level on the folds of the East African Rift Valley in its central and western regions. Kenya produces several equatorial and tropical crops including coffee, tea, maize, pyrethrum, tobacco, beans, mangoes, coconut, and an assortment of flowers. Most of these must be dried either before storage or during processing to the final useable product. For Kenya, the average yearly insolation is about 0.7 kW/m^2 and the average yearly sunshine is 7 hours/day. Thus, a great potential exists for meeting some of the crop drying requirement by solar energy.

However, regional variation in insolation, high relative humidity (RH) levels (morning national yearly average RH is 70%), and the coincidence of rain (national yearly average of 800 mm) with the harvesting period limit the number of crops that can be solar dried in a given region of Kenya. Additionally, some crops (Table 1) have unique drying requirements, e.g., fast drying is needed to avoid crop quality deterioration.

---

[1] Mechanical Engineering Department, University of Nairobi, Nairobi, Kenya.

Table 1. Potential crops for solar drying in Kenya.

	Coffee	Maize	Tea	Pyrethrum
Quantity (kt/year)	140	120	81	9
Moisture content (% wet basis)				
Wet	55	22	74	70
Dry	11	13	4	15
Optimum drying time (hours)	NC[a]	NC	12	48
Harvest period of year (major)[b]	Apr-May	Aug-Oct	Aug-Oct	Sep-Nov
Rainfall during harvest (mm/month)	149	94	94	92
Relative humidity (%)	79	78	78	76
Global insolation (MJ/m^2 per day)	9.9	8.3	8.3	9.1
Sunshine (hours/day)	7	6	6	7
Maximum ambient temperature (°C)	25	24	24	24

[a] NC = not critical.
[b] Some crops are produced under irrigation year round.

Nationwide, crop drying by most subsistence farmers takes the form of open-air sun drying. However, various mechanical dryers have been tried with varying degrees of success by cooperative societies and commercial farmers. To replace some of the ineffective ones, intense research has gone into solar crop dryers: recently, solar dryers for maize (Othieno 1985), coffee (Trim and Brenndorfer 1985), and pyrethrum (Sebbowa 1985) have been particularly important.

Crop Dryers in Kenya: A Case Study of Pyrethrum

This case study of pyrethrum in Kenya is used to highlight some of the techno-socioeconomic reasons underlining the failure of solar crop dryers to gain popularity in Kenya, and perhaps other developing countries. On a yearly average, Kenya produces 40,000 t of wet pyrethrum in the region shown in Fig. 1. The Kenyan product makes up more than 80% of the world's demand of this important base of "safe insecticides." However, the Kenyan crop is normally harvested at moisture levels in excess of 70% (wet basis, WB) and must be dried to below 40% (WB) in the first 48 hours and finally to 13-10% in the next 12 hours for safe storage and processing. Thus, the search for an effective pyrethrum dryer must continue if the cost of evaporating this large quantity of water from pyrethrum is to be reduced.

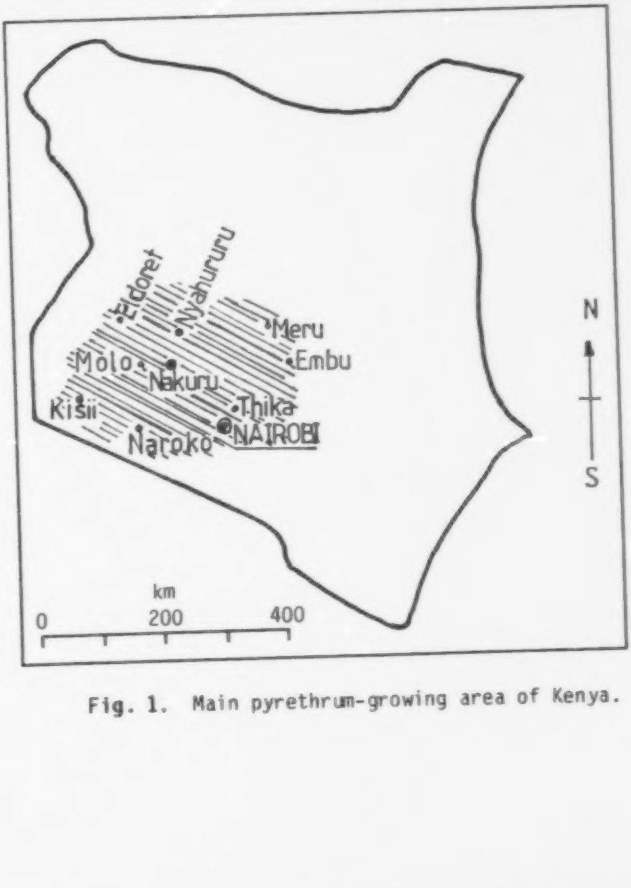


Fig. 1. Main pyrethrum-growing area of Kenya.

Previous and Current Crop Dryers in Kenya

Open-air Sun Drying

All Kenyan crops, except tea and tobacco, that must be dried could be dried by the traditional open-air sun drying. This involves spreading the crop either on the bare ground or on some protective material on the ground, e.g., sacking, or on wire mesh, which is often raised above the ground. Indeed about 55% of the Kenyan pyrethrum crop is dried this way by small-plot farmers. Crop contamination and spoilage occur and labour is intensive. For mass-production farmers, the requisite drying space has often proved prohibitively large. Additionally, for some crops, the rate of drying possible with open-air sun drying is too slow and quality would deteriorate due to rotting. For pyrethrum production in excess of 500 kg/week (WB), a mechanical dryer has always been necessary.

Oil-fired Pyrethrum Dryers

Oil-fired pyrethrum dryers (Fig. 2) were very popular until the early 1970s. The possibility of controlling the heat source, and hence heat input, and the mechanical blower ensured that these were very fast and effective dryers. However, the rocketing cost of oil, among other essential components, has long since priced oil-fired dryers out of reach of all pyrethrum farmers.

Wood-fired Pyrethrum Dryers

Variants of the wood-fired dryer (Fig. 3) replaced the oil-fired dryers. Although wood-fired dryers are popular and common on pyrethrum farms in Kenya, they are now threatened by the ever-dwindling national forest reserves -- their main source of fuel. The price of fuelwood due to scarcity in some areas is already proving a burden for quite a few farmers. Other operational costs, e.g., regular replace-

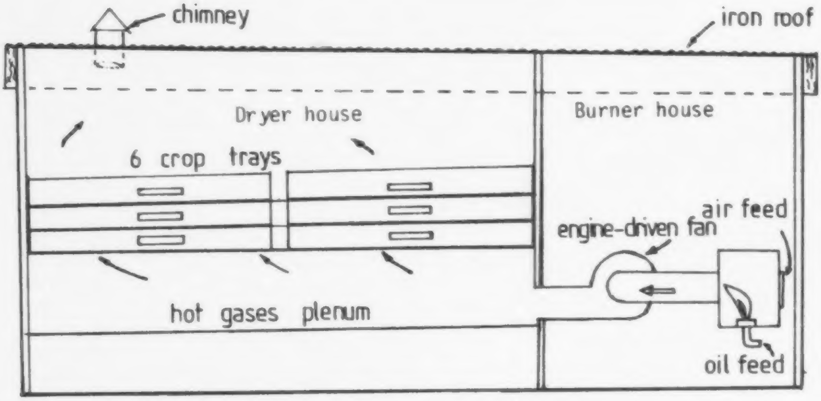


Fig. 2. Oil-fired pyrethrum dryer -- capacity 500 kg (WB), drying time 24 hours.

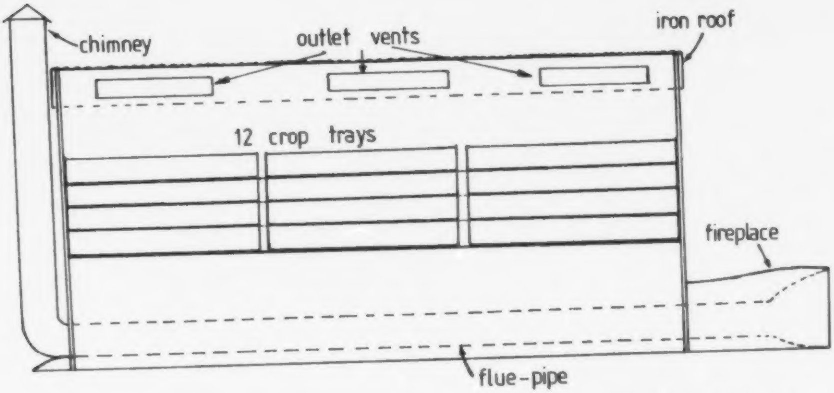


Fig. 3. Wood-fired pyrethrum dryer -- capacity 300-500 kg (WB), drying time 24-36 hours.

ment of flue pipes and the ever present fire-risk, all point to the need for a search for some other type of dryer. In a few cases, farmers have used charcoal-burning dryers. However, their shortcomings are basically the same as for wood and their use has not caught on in Kenya.

Natural-convection Dryers

Various solar dryers with natural convection and augmented direct heating (Fig. 4) have been studied both by the Pyrethrum Board of Kenya (PBK) and the University of Nairobi (UON). The UON studies were done on a design (Fig. 5) that is convertible to forced convection operation (described later). In both cases, the test results showed inadequate drying, especially during the rainy months, which coincides with the peak of pyrethrum harvesting in Kenya (Fig. 6). In this respect, it was hoped that the Tanzanian design first reported in 1984 (Mrema 1984) would provide some answers. In Kenya, at least at UON, the thrust has been toward forced-convection solar dryers.

Forced-convection Solar Pyrethrum Dryer

Background Design Data

After identification of the crop or crops of interest, in this case pyrethrum, and their producing regions (see Fig. 1), the next step should be to ascertain the prevailing average insolation, sunshine hours, maximum outside temperature, relative humidity, and rainfall (Table 2). It is also important, however, to determine the levels of these parameters in relation to the drying period (Fig. 6). The "whole area means" in Table 2 do not differ much from the mean national values except for relative humidity and rainfall yearly distribution (these are plotted in Fig. 6 on a monthly average basis for the whole year). The average delivery rates of dried pyrethrum crop at the PBK depot are included in Fig. 6 to indicate the major

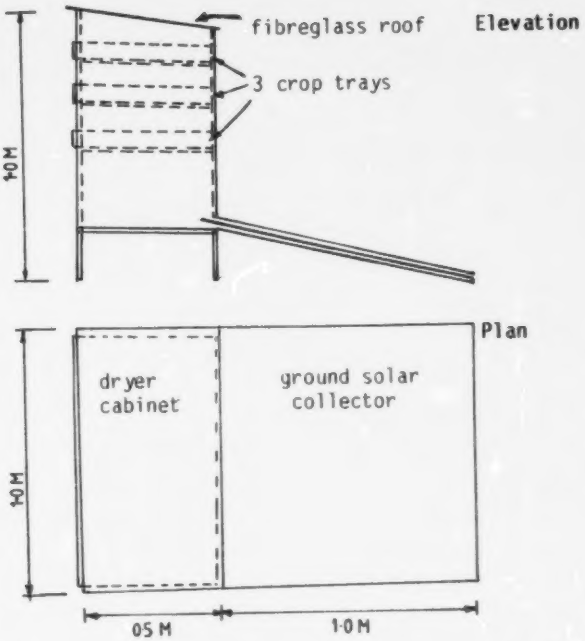


Fig. 4. Natural-convection pyrethrum solar dryer -- capacity 40 kg (WB), drying time 30-50 hours. Because its capacity is too low and drying rate too slow, this dryer has not been adopted.

drying period in relation to the weather parameters -- farmers usually deliver their dry crop within 2 weeks of harvest (Sebbowa et al. 1985).

Design Details of the Solar Dryer

The UON-designed pyrethrum dryer (Fig. 5) has a capacity of 400 kg (WB). (Technical details have been reported elsewhere, Sebbowa 1985.) In the natural-convection mode, the solar collector is coupled directly to the dryer, i.e., the electric fan is excluded. In the forced-convection mode, two configurations are possible: either a single solar collector (located on the ground) and direct solar rays through the Perspex roof onto the top layers of crops; or no direct solar rays on crops, i.e., with roof solar collectors augmenting the ground solar collector for air heating. In this latter mode, the total solar energy collection area is nearly triple that in the other two cases.

Performance and Test Results

Typical drying rates for pyrethrum during a predominantly rainy period (rain having fallen at least 50% of the whole drying period) and a predominantly sunny period are shown in Fig. 7. On the basis of

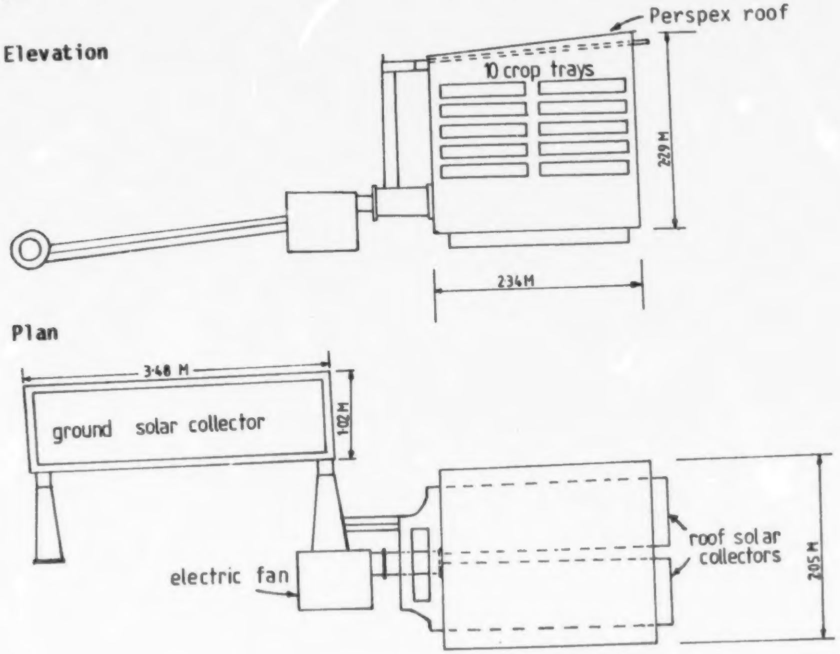


Fig. 5. Solar pyrethrum dryer -- capacity 400 kg (WB), drying time about 36 hours.

these results, a few conclusions can be drawn. The results are based on tests carried out over 3 years in one prototype and comparison is only for corresponding months of different years.

First, forced-convection drying is more than 5 hours (16%) faster during the sunny period than during the rainy period. Second, using forced convection, the difference between the three solar collectors (without direct sun rays on the crops) and the one solar collector (with direct sun rays on the crops) is not significant. The latter is cheaper and the dryer is easier to fabricate. Third, natural convection does not induce a sufficiently rapid drying rate to attain a moisture content of below 40% (WB) within the 48 hours (about 15 drying hours) after harvesting. Indeed, the rainy period test was abandoned to prevent complete loss of the crop by rotting.

Unique Techno-socioeconomic Limitations to the Dryer

There are three major technical limitations to this particular solar crop dryer. First, its failure to perform well during the rainy periods: the low drying rate often leads to mild crop rotting that, with the attendant loss in quality, would dissuade farmers from using it because the crop is purchased from them on a quality-quantity basis. Second, during the nights the crop may be rewetted by early morning dew resulting from condensation of moisture from the air.

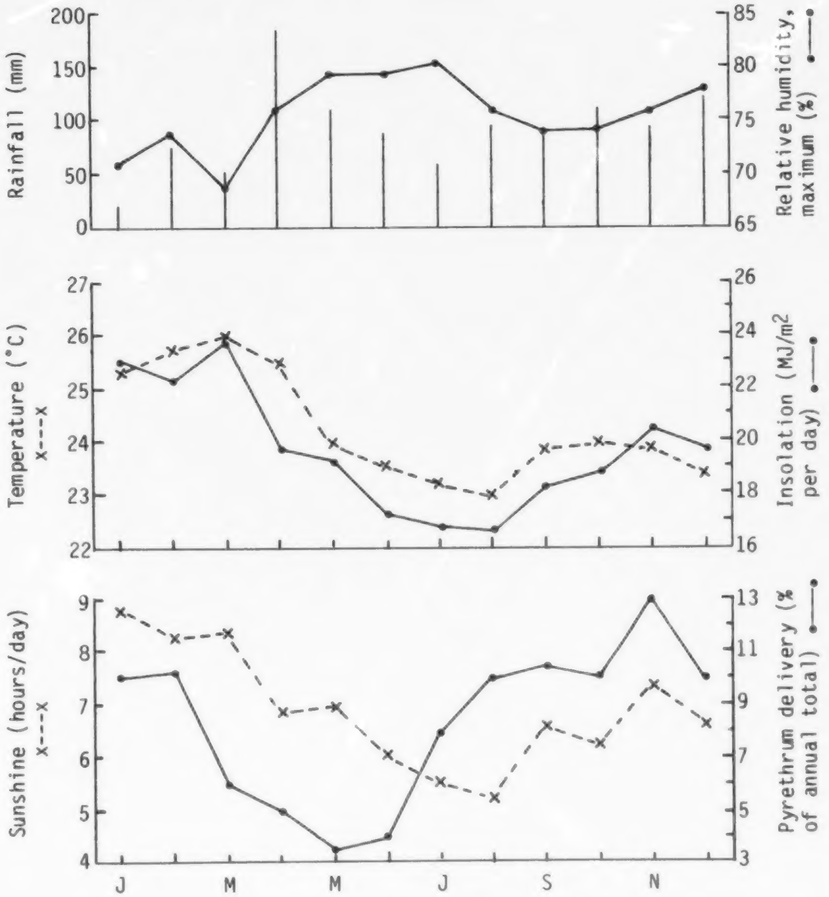


Fig. 6. Monthly average weather data for Kenya's pyrethrum-growing area.

Third, the glass cover is easily cracked: although this problem can be reduced to some extent by the use of compressible materials between the glass cover and the solid frame of the collector, thermal stresses, if not properly allowed for, lead to the breakage of the glass cover sooner or later.

Socially, this particular design has not been tested. However, a bad reputation hangs over it from previous unsuccessful solar dryers that were tried in the late 1950s and early 1960s.

Economically, two limitations are perhaps specific to this dryer and to Kenya.

Table 2. Annual average weather conditions of the principal pyrethrum centres (see Fig. 1).

Centre	**Location**			**Temperature (°C)**		**Radiation (MJ/m^2 per day)**	**Sunshine (hours/day)**	**RH (%)**		**Rainfall (mm/month)**
	Latitude	**Longitude**	**Height (m)**	**Maximum**	**Minimum**			**Morn- ing**	**After- noon**	
Meru	00°05'S	37°39'E	1538	25	14	19.08	7	80	61	85
Embu	00°30'S	37°27'E	1508	25	15	18.31	7	81	53	94
Thika	01°01'S	37°06'E	1477	26	15	19.40	7	81	50	85
Nairobi	01°18'S	36°45'E	1798	25	14	18.57	7	79	54	77
Naroko	01°08'S	35°50'E	1890	26	9	18.49	8	NA[a]	NA	54
Kisii	00°41'S	34°47'E	1732	26	16	NA	7	70	64	160
Molo	00°14'S	35°43'E	2523	21	7	NA	NA	83	79	NA
Nakuru	00°16'S	36°04'E	1873	26	11	24.10	7	NA	NA	78
Nyahururu	00°02'N	36°17'E	2369	22	8	NA	7	71	53	90
Eldoret	00°34'N	35°18'E	2154	24	11	22.70	7	74	49	116
Whole area	--	--	1886	24.6	12.0	20.10	7.1	76.4	57.9	93.2

[a] NA = not available.

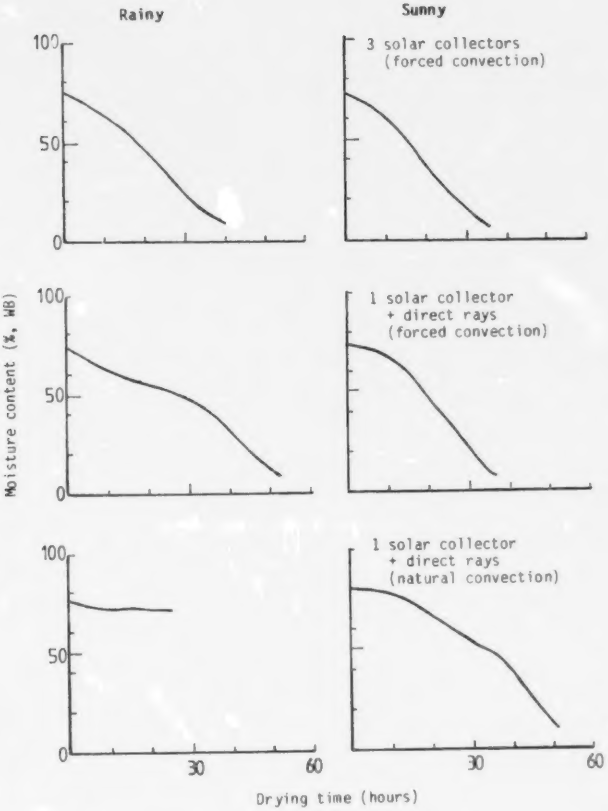


Fig. 7. Specimen test results of moisture content against drying time.

First, the dimensions of the materials that were available cheaply limited the size of the dryer components and, hence, limited its performance. Usually, in Kenya, both glass and corrugated iron sheets (for collector plates) are sold in standard sizes at low government-controlled prices. However, the standard sizes (0.92 m x 2 m or x 2.5 m) do not easily fit the required optimum collector area. The materials are available in other dimensions but the prices are very high.

The second constraint peculiar to this dryer is the rather high price (KSH 14,000 in 1986 prices; 1 U.S. dollar [USD] = 16.5 Kenyan shillings [KSH]), which restricts it to farmers working plots larger than 12 ha. In the absence of soft-loans, the dryer must be aimed at farmers likely to realize at least five times its price in a year. This is to allow for other necessary expenses (e.g., school fees, etc.) without straining the farmer's budget.

Recommendations

Despite its limitations, this dryer is capable of meeting 70% of the pyrethrum drying requirements; the rest of pyrethrum being harvested when it is too rainy for solar drying. To overcome the technical shortcomings, a hybrid dryer has been designed at UON (Fig. 8). This dryer uses solar energy as the primary energy source and firewood as an auxilliary source during periods when rain or overcast reduce the effectiveness of solar drying. Inclusion of the auxilliary energy source in the design is more or less standard procedure for solar energy systems (e.g., water heaters, etc.) that must provide heating at specific times come rain or shine (ASHRAE 1976).

To reduce the public stigma attached to solar crop dryers, a program of gradual reintroduction of solar crop dryers is recommended. The first step would be to install specimen dryers at agricultural demonstration stations, where the system can be seen at work. This should be followed by installments at some chosen successful farms.

To minimize costs, at least in Kenya, components that use materials to be purchased off the shelf (e.g., glass sheets, etc.) must be designed to use the standard sizes whose prices are controlled by government because they are used in other basic requirements such as houses.

General Limitations of Solar Crop Dryer Research

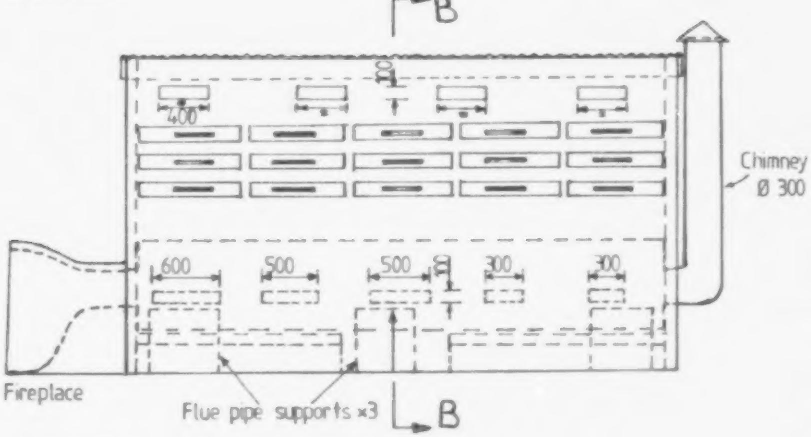
Identification of End Users

Because the current work on solar devices in general started with the so-called energy crisis of the 1970s, it has tended to be directed to energy per se rather than the end user. Thus, solar dryers have been designed first and, subsequently, crops that could be dried in them identified. This, in some cases, has led to solar dryers whose supposed end users will have nothing to do with them: either because of traditions or because the dryers adversely alter some of the qualities of the dried items.

In particular, there is a serious mismatch between the costs of solar crop dryers and the end user's financial resources. A farmer producing 1000 kg of wet pyrethrum per year, and earning KSH 3750 from it, cannot afford a solar dryer costing anywhere near KSH 1500 because other domestic financial obligations must be met and credit facilities are not available to spread the cost of the dryer over a longer period. In addition, open-air sun drying is traditionally suitable for the purpose. The philosophy of using several small dryers (e.g., Fig. 4) for the mass-production farmer often ignores the increased maintenance costs of multiple systems and, in any case, these may end up taking as much space as the cheaper open-air sun drying would require.

Parastatal organizations, in some cases, have encouraged the design of large solar dryers with imported components. Although such parastatals can get their foreign components at subsidized rates through government-to-government grants, local commercial concerns that pay the full taxes are not enthusiastic especially if their experience with dryers is based on the one-off system available at the local parastatal headquarters.

Elevation


B
400
Chimney
Ø 300
600
500
500
300
300
Fireplace
Flue pipe supports ×3
B

Section B-B

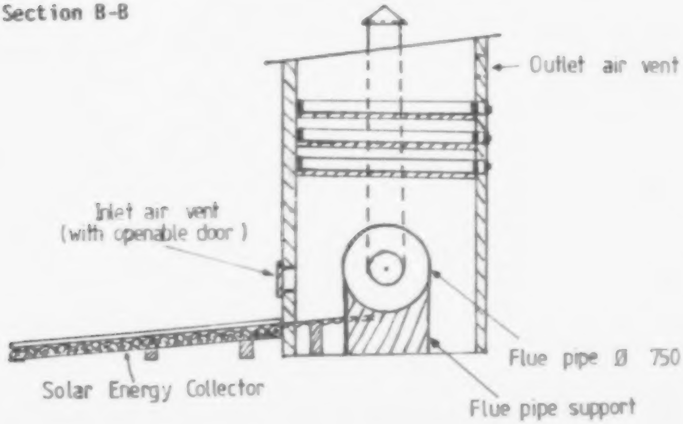

Outlet air vent
Inlet air vent
(with openable door)
Flue pipe Ø 750
Solar Energy Collector
Flue pipe support

Fig. 8. Hybrid solar-wood pyrethrum dryer (dimensions are in millimetres).

Research Methodology

Perhaps the single most basic problem is lack of sufficient, and sufficiently accurate, data. Failure to survey the intended end-users at an early stage to find out their expectations is a fundamental problem for innovative designs. Often researchers do not scrutinize crop-production information given by local bureaucrats, who have been known to adjust the numerical data to suit the prevailing political climate. Thus, now and then, research in solar crop drying has been aimed either at nonexistent "large quantities" of crops or at crops for which existing drying methods are more than sufficient.

Even where crop data are valid, the insolation and other pertinent weather data are either lacking or inaccurately kept. Even inaccurate data can be modified to make sense, but usually the researcher must gather the data at the same time as the work on the dryer is continuing. Now, true insolation and weather patterns must be averaged over a period of at least 3 years, which the researcher never has, and the use of modified or short-period (1-year) data often yields errors in design.

Some researchers have been misled into adopting the theory that a small laboratory prototype can reflect a full-sized dryer to be used in the field. Admittedly, modeling is an acceptable engineering design technique but only if the laws of similitude are carefully followed. With the fluctuations of the fundamental parameters, such as insolation and flow rates, encountered in solar crop drying work, miniature models are certain to be disappointing.

Finally, funding agencies have failed to accept that researchers are often university-based or engaged in other work and thus work only part time on the various research projects. Demand for frequent reports, whether for accounting or other purposes, may lead to one of two things: the researcher either concentrates on report writing and neglects the actual research or performs hasty experiments with errors and misinterpreted results.

Technology Exchange

The research results from various institutions are not readily available to researchers. Research coordinators in many developing countries must be more forthcoming in communicating the available research findings to other researchers who might benefit from them. Additionally, senior researchers might consider laying more emphasis on providing better leadership in actual experimental research and presentation of results. At present, too much emphasis is put on policy statements by senior researchers and academics in the developing world.

The lack of cooperation between local industry and researchers continues to hinder progress not only in research but also in development. Local industry is well placed to judge the suitability of various new inventions, such as the solar crop dryers, yet most researchers ignore local industry until the end of the research process when it is expected to commercialize whatever products have been developed. Understandably, industry has so far been reluctant.

The North-South flow of technology leaves much to be desired. Fresh graduates from the North travel South as experts as part of their nations' grant or aid packages yet expertise in the South is not used. For half the expense of these "experts," the expertise in the South could be used for productive research and funds would be available for product commercialization, etc.

Technological information transfer on the global scale remains scanty. The Brace Research Institute and United Nations Industrial Development Organization (UNIDO) have an excellent policy of mailing, regularly, research findings to potentially interested parties. Other research organizations might consider establishing equivalent mailing lists or expanding existing ones that are currently too limited. In this manner, a larger audience will get access to important results and findings that might be of interest to more research workers than those currently getting them. Researchers often are not aware of the availability of vital and essential information about their work that is available in the secretariates and headquarters of agencies in the North.

For research equipment to give meaningful results, it must be calibrated regularly. This is particularly a problem where the equipment is manufactured in the North and used in the South. In many developing countries, equipment used for research does not receive regular checks for accuracy. A researcher with only one piece of equipment has no way of knowing whether that equipment is giving accurate readings or not, unless it can be regularly calibrated.

Conclusion

At least for the Kenyan pyrethrum farmer, a solar crop dryer is needed because the amount of drying involved is substantial and the alternative methods to solar drying are costly. Technical problems on the prototype solar dryer still exist but can be overcome. The hybrid dryer (Fig. 8) mentioned here is one way of doing this, but other solutions are also possible.

In general, solar crop drying has been and still is plagued by various problems. Some of these could be overcome.

- A first step in the research process is proper definition of the crops needing drying.
- Gathering and analysis of insolation (and other pertinent) data must become a priority.
- Researchers must consult local industry at an early stage in the product development.
- Financial or other compensation for researchers should be commensurate with the time and effort spent on the research.
- Meaningful information transfer should be encouraged through regular periodic reports of research findings and progress covering all pertinent research work.
- There must be a shift from the "North expert goes South with a few black boxes" system of support to one of training the South's potential experts, be it in the North or South, to a level of self-sufficiency.
- Strategic centres must be set up in the South to permit calibration of apparatus to ensure that results and data gathered by researchers on older equipment is valid.

I am convinced that, unless most of these are attended to, solar crop drying in most developing countries will continue to be an unsuccessful venture and unreported results will not provide solutions to the crop-drying problems in the developing world.

Acknowledgment -- I acknowledge the financial support of the Kenyan National Council for Science and Technology, the Commonwealth Science Council, the British Overseas Development Administration, and the University of Nairobi.

References

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). 1976. Method of testing solar collectors based on thermal performance. ASHRAE, New York, NY, USA. Technical Report Standard 93-P (1976).

Mrema, G.C. 1984. African energy programme: solar crop drying project -- an overview of the project. Paper presented at the African Energy Programme Review Meeting, Harare, Zimbabwe, 15-20 October 1984. Commonwealth Science Council, London, U.K.

Othieno, H. 1985. Optimisation of solar air heating collectors used for crop drying. In Renewable energy developments in Africa: Proceedings of the International Conference on Research and Development of Renewable Energy Technologies in Africa, Mauritius, 25 March-1 April 1985 (Vol. 2). Commonwealth Science Council, London, U.K.

Sebbowa, F.B. 1985. Design considerations and prototype tests on a pyrethrum flow solar energy dryer. In Renewable energy developments in Africa: Proceedings of the International Conference on Research and Development of Renewable Energy Technologies in Africa, Mauritius, 25 March-1 April 1985 (Vol. 2). Commonwealth Science Council, London, U.K.

Sebbowa, F.B., Preston, K., Gwara, N. 1985. Field visitation report: the Kenyan pyrethrum farmers' needs. University of Nairobi, Nairobi, Kenya. Unpublished report.

Trim, D.S., Brenndorfer, B. 1985. Development of a three stage solar drying system for coffee. In Renewable energy developments in Africa: Proceedings of the International Conference on Research and Development of Renewable Energy Technologies in Africa, Mauritius, 25 March-1 April 1985 (Vol. 2). Commonwealth Science Council, London, U.K.

SOLAR DRYING IN MALI

Modibo Dicko[1]

Abstract *-- Mali's geography and climate, the agricultural products usually dried, and traditional methods of drying are reviewed. Research activities and on-site experiments in solar drying in Mali are described and a future research program on solar drying is suggested.*

Introduction

Preservation of foodstuffs is vitally necessary in Mali because production is mainly seasonal whereas consumption is year-round. Drying is practically the only preservation method in widespread use because of its simplicity and low cost. The climate in Mali, with its long dry season characterized by high ambient air temperatures and very low relative humidities, is particularly favourable to the technique of drying, whereas other preservation techniques, such as refrigeration and freezing, are more difficult and less economical. The techniques and drying times vary slightly depending on the product, but all the techniques employ natural drying because of the combined action of the wind and sun on the exposed products. The disadvantages of natural drying are well known, and include lack of hygiene, inadequate security, and losses that are often considerable. Improvements in drying techniques are, therefore, of vital economic importance.

This paper is concerned first with analyzing the meteorological data that influence drying conditions and, second, with present drying practices in Mali. The third part is devoted to research in Mali to improve solar dryers. The fourth part concerns experiments in improved drying conducted in a rural area. Finally, the last part is concerned with a future research program on solar drying in Mali.

Climatic Conditions

Mali is a vast country, covering an area of 1.24 million km^2, whose extremes reach from 4.3°E to 12.5°W, and from 10.5° to 25.0°N. Mali is situated in the heart of western Africa. Climate and vegetation range from the types found in the Sahara to those found in Guinea. The dry season extends from October to May and the rainy season from June to October.

For several decades, the meteorological service has provided measurements of air temperature (Table 1) and humidity (Table 2), wind speed (Table 3), and hours of sunshine (Table 4) in a number of towns and cities across the country.

---

[1] Laboratoire de l'énergie solaire, Bamako, Mali.

The intensity of solar radiation has, however, only been measured since 1981. Measurements have been made in Bamako, Bougouni, San, and Tombouctou by the meteorological service, and in Bamako, Bougouni, Gao, Nioro, and San by the Laboratoire de l'énergie solaire. Examination of the compiled data for 1981-1984 reveals that the those gathered at Bamako by the Laboratoire de l'énergie solaire are most reliable. Mean values calculated on the basis of these data are given in Table 5. Statistical analysis gave the following relationships (Dicko 1986):

$$H/H_o = 0.28 + 0.28\ (n/N) \qquad [1]$$

$$H_d/H = 0.432 - 0.32\ (K_t) \qquad [2]$$

where

H = monthly average of total daily radiation,

H_o = monthly average of total daily radiation above the atmosphere,

n = monthly average of daily hours of sunshine,

N = theoretical monthly average of daily hours of sunshine (Duffie and Beckman 1980),

H_d = monthly average of diffuse daily radiation, and

K_t = monthly average of insolation fraction.

These relationships should be used for the southern half of the country, but for the northern desert we recommend the relationship established for Tamanrasset in southern Algeria (Duffie and Beckman 1980):

$$H/H_o = 0.30 + 0.43\ (n/N) \qquad [3]$$

Current Drying Practice

A wide variety of food products are dried. The techniques and drying times vary slightly depending on the product, but all the techniques employ natural drying because of the combined action of the wind and sun on the exposed products (Duffie and Beckman 1980; Dicko 1986).

Cereals

Traditional drying methods comprise three stages. In the first stage, the mature grain is harvested rather late in the season, and has already started to dry. This practice results in many losses due to shelling of the grain and lodging of the crop. In the second stage, prior to threshing, the harvested grain is tied in sheaves then arranged in conical piles in suitably prepared areas in the field. The conical piles can be 2-4 m in diameter and 1.5-2 m high. This stage lasts 2-4 weeks depending upon the availability of people for threshing. In the third stage, after threshing, the crop is transported to the village where it is spread out on specially prepared surfaces (hard-packed surfaces, matting, or sacking) and sun-dried for several days. Maize cobs are spread on wooden or straw platforms that are placed on the roofs of the houses.

Table 1. Mean monthly and annual air temperatures (°C).

Towns	Mean annual	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Bamako	28.4	25.5	28.0	30.9	32.4	31.9	29.1	28.0	26.0	26.2	37.8	27.2	28.0
Kayes	29.6	25.4	28.0	31.2	34.1	35.5	32.1	28.7	27.9	27.8	29.4	28.9	25.8
Ségou	27.9	24.0	26.6	29.7	32.2	32.7	29.0	27.6	26.5	27.0	27.6	27.2	24.3
Gao	29.2	22.6	25.2	28.8	32.3	32.1	34.7	32.9	29.8	31.3	31.7	27.2	21.2
Tombouctou	29.8	22.6	25.4	28.5	31.8	34.3	33.9	31.5	35.5	31.2	31.7	28.3	22.8
Kidal	28.9	19.5	22.2	30.5	29.3	34.3	34.9	32.5	31.2	32.3	31.1	27.9	20.9

Table 2. Relative humidity of air (%).

Towns	Mean annual	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Bamako	52	28	24	25	34	51	68	77	81	79	69	51	36
Kayes	44	29	19	17	19	30	53	72	79	79	69	43	28
Ségou	49	31	25	26	28	43	58	73	80	77	65	46	36
Gao	31	22	18	17	18	25	37	49	58	54	33	24	23
Tombouctou	36	27	23	22	20	27	40	55	65	57	35	28	30
Kidal	27	23	18	20	21	16	24	38	47	36	26	26	25

Table 3. Mean wind speed (m/sec), 1961-1970.

Towns	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Mean annual
Bamako	2.1	2.4	2.4	2.4	2.8	3.4	3.4	2.9	2.1	3.0	2.0	1.8	2.6
Gao	4.2	4.3	4.4	4.3	4.3	5.0	5.1	4.4	4.1	3.7	3.9	3.9	4.3
Kayes	1.9	1.9	2.0	2.3	2.7	3.1	2.5	1.9	1.5	1.4	1.4	1.6	2.0
Mopti	1.3	3.4	3.6	3.4	3.5	3.5	3.5	2.5	2.2	2.1	2.4	2.5	3.0
Ségou	2.4	2.5	2.5	2.2	2.2	2.5	2.0	1.5	1.2	1.1	1.8	2.2	1.8
Tessalit	4.6	5.0	4.8	4.5	5.0	5.0	4.9	5.0	4.3	4.5	4.2	4.0	4.7

Source: National Meteorological Service, Mali.

Table 4. Monthly sunshine (hours[a]) for some major towns in Mali.

Towns	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Bamako	266.5	242.2	269.9	241.8	216.1	204.5	194.6	163.7	197.9	230.2	243.0	219.3	2688.7
Gao	275.8	264.4	288.3	293.7	285.7	265.7	276.0	266.9	273.2	291.5	289.2	269.8	3339.6
Kayes	253.0	233.4	300.8	286.3	253.7	218.6	197.4	187.4	208.9	241.0	247.6	201.4	2829.5
Mopti	229.7	224.8	251.4	249.6	233.7	240.4	255.9	205.9	231.0	259.5	248.5	190.4	2790.8
Ségou	286.1	269.2	296.0	281.3	271.0	273.7	251.5	225.7	247.3	293.9	282.8	277.3	3255.8
Tessalit	299.7	289.0	315.4	311.7	305.7	265.6	293.9	285.0	272.6	300.3	269.2	258.9	3447.0

Source: National Meteorological Service, Mali.

[a] Measured to nearest 0.1 hour (≡ 6 min).

Table 5. Mean monthly total, diffuse, and direct solar radiation at Bamako (kWh/m^2 per day), 1981-1984 average.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Total radiation	4.77	4.57	4.57	4.35	4.06	5.90	3.90	3.88	4.11	3.93	3.97	4.03
Diffuse radiation	1.04	1.23	1.30	1.35	1.14	1.36	1.24	1.34	1.11	0.98	0.77	1.00
Direct radiation	3.73	3.34	3.27	3.00	2.92	2.54	2.66	2.54	3.00	2.95	3.20	3.03

Source: Laboratoire de l'énergie solaire, Mali.

This method has the following disadvantages: shelling and lodging due to late harvesting; risk of theft during drying in the field; infestation by dust, insects, and wandering animals; risk of rewetting from late rains; and lack of space. The drying period extends from October to November.

Normal annual production is between 800,000 and 900,000 t for all the cereals cultivated.

Groundnuts

After being unearthed, the groundnuts are arranged in small heaps in the field with their pods turned out toward the open air. One week later, the groundnuts are stacked on raised wooden or straw platforms so that the air can circulate up through the product. This circulation is enhanced by leaving a passage through the middle of the stack. Stack drying lasts for 2-3 weeks. The pods are then separated from the stalks, and the groundnuts are transported to the village where they are spread out on wooden or straw platforms on the roofs of the houses, or in specially woven conical baskets through which air can pass easily to accelerate drying. This technique suffers from the same disadvantages as that used for cereals. The drying period is the same. Annual production is estimated at 100,000 t.

Tobacco

Virginia-type tobacco is dried in so-called "flue curing" dryers that consist of a wood-fired oven with a stonework drying chamber. This very complex process lasts for several days and between 6-12 steres of wood (1 stere = 1 m^3 of stacked cord wood) are burned per oven batch. The major disadvantage of this technique is the enormous wood consumption. Other types of tobacco are open-air dried by suspending the tobacco leaves from branches in a confined space. Drying can take up to 45 days. This technique requires virtually no further improvement. The drying period extends over the month of October for the rainy season crop and over the months of January and February for the out-of-season crop. Annual production is about 250 t.

Vegetables and Fruit

Vegetables are dried in small quantities within the family unit, and each woman dries her vegetables separately. The vegetables are mainly okra, chillies, onions, and to a lesser extent tomatoes. The vegetables are spread out in a single layer in the sun on clean stones, mats, or straw and sometimes on the roofs of barns. Drying is very rapid and takes only 1-2 days.

Okra and chillies are dried whole. The dry product is then crushed and ground to powder. Onion bulbs and leaves are crushed, then rolled into small balls that are then dried in the sun. They become very brown and the final product is poor quality. The drying period is from February to April.

Traditionally, fruits are not dried. They are eaten fresh during the harvest season and, afterwards, people do without. Overproduction and lack of means of preservation results in much loss by deterioration.

Fish

Fish drying comprises the following operations: cleaning, chemical treatment, fermentation, and drying. The fish are scaled and gutted, and the heads removed. They are then opened at the backbone and rinsed in water. After cleaning, the fish are treated chemically. Introduced to the fishing community by the Opération Pêche de Mopti, chemical treatment consists of dipping the fish for 2-3 hours in a solution of "gardonan," a chemical product manufactured by Shell Chemical. This treatment reduces the losses due to insects from about 30-40% after 2 months of storage to only 10-15%. After this stage, the fish are fermented, which gives the dry fish its "high" taste that is popular among Malians. The fish are first piled in bulk for several hours in the hot season, or for several days in the cool season, to start the fermentation. This operation is often combined with dipping the fish in "gardonan" water. The fish are then spread out on a bed of dry straw, with the open side of the fish exposed to the sun for drying. During the rainy season, the fish are spread out on the roofs of sheds that are specially built to protect the fish from humidity from the ground. Drying time extends for 2-3 days in the dry season to almost 7 days in the rainy season. It also varies as a function of the size and type of fish. The drying period covers practically the whole year, although the catch is markedly lower during the high water period (June to September).

The disadvantages of this technique are the enormous losses due to attack by voracious fly larvae during drying and storage, as well as soiling by dust and sand. The annual catch is estimated at 100,000 t on average for a normal year. The proportion of fish dried varies according to region. In the area around the artificial lake of Sélingué, for instance, the proportion of fish dried is 10% of the total catch, or an average of 1550 t annually.

Meat

Dried meat is commonly consumely by the nomadic peoples of northern Mali. Traditionally, the meat is cut into thin slices and then spread out directly on the desert sand. Because of the intensity of the winds and sun in these regions, drying is very fast and lasts for only 1-2 days, but the meat is soiled by an encrustation of sand.

An improved version of this natural drying technique was introduced 2 years ago. The slices of meat are first immersed for 1 minute in a boiling salt solution and then placed on racks that are suspended in an area entirely enclosed with mosquito netting. This improved method does not, however, protect the meat against dust deposited by the wind.

Solar Dryers

The first systems studied were natural-convection solar dryers. The indirect dryer (Fig. 1a) is made of steel sheeting and has a glass-covered collector of 1.28 m^2. Its load capacity is about 9.5 kg of fresh product. The Taost dryer (Fig. 1b) is made of wood (20-mm plywood) and has a transparent plastic cover of 2 m^2 in surface area. Its capacity is about 15 kg of fresh product. The Greenhouse dryer (Fig. 1c) is a wooden parallelepiped structure, 3 m long, 2 m wide,

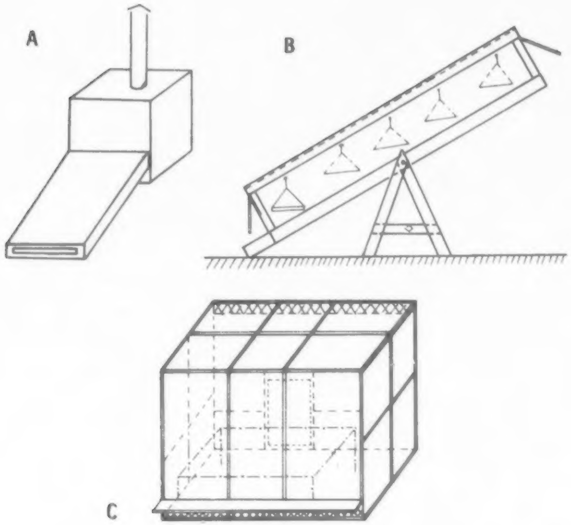


Fig. 1. a: Indirect dryer, b: Taost-type dryer, c: Greenhouse-type dryer.

and 2 m high, covered with black polyethylene on its north side and transparent polyethylene on its other sides. Its capacity is about 45 kg of fresh product. These dryers were tested with various products, in particular fish, meat, mangoes, onions, okra, and tomatoes (Dembele 1982; Traore 1982).

Results of Solar Drying Research

Products commonly dried in Mali can be divided into two classes: those that are dried in thin layers, such as fish, meat, and vegetables, and those that are dried in thick layers, such as cereals. Products in the thin-layer class have attracted the attention of the Laboratoire de l'énergie solaire because they are more humid and perishable in the fresh state than products in the thick-layer class. Considerable effort has been expended to perfect the thin-layer drying systems in Mali. The tests led to three main conclusions.

First, the indirect dryer (Fig. 1a) proved to be relatively inefficient because the drying time was longer than in open air. Some of the very humid products, such as tomatoes, start to deteriorate before drying is complete. This is certainly due to bad ventilation caused by the chimney effect. This technique still needs to be optimized to overcome this disadvantage.

Second, the direct-type Taost (Fig. 1b) and Greenhouse (Fig. 1c) dryers proved to be more efficient (Figs 2 and 3). These good results can be explained in part because the product reached a higher temperature due to direct absorption of solar radiation. It should also be

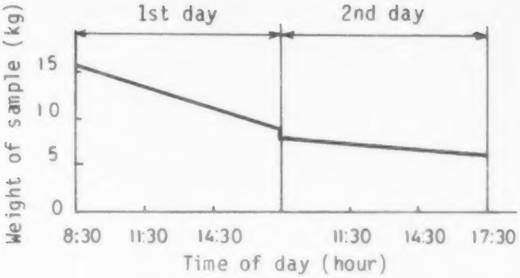


Fig. 2. Drying curve for fish in the Taost dryer.

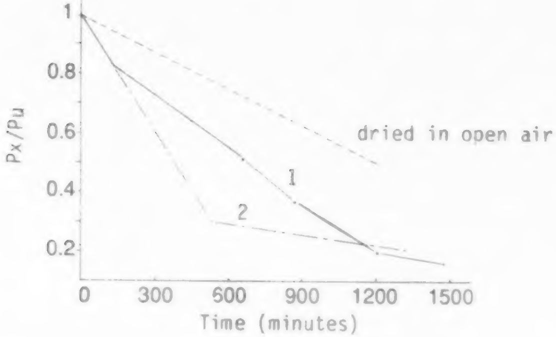


Fig. 3. Drying curve for three samples of mangoes: 1 and 2 in the Taost dryer on different racks; and open-air drying. (Px = weight as a function of time and Pu = initial weight.)

noted that the configuration of these dryers promoted good ventilation, and hence small pressure losses, and that the air column is continually heated, unlike that of the indirect dryer (Fig. 1a).

Third, because the dryers were intended for the rural community, we attempted to reduce the cost by making the covers from transparent plastic rather than glass. Three types of material were tried: polyethylene (produced in Mali), a silicon fabric manufactured by Dow-Corning (imported), and mylar (imported). These tests showed that polyethylene has a useful life of 2-3 months, whereas the useful life of the silicon fabric and mylar is almost 2 years. From the standpoint of cost, mylar is as expensive as glass, but the silicon fabric is quite cheap. For this reason, we recommend the use of the silicon fabric material.

The main disadvantage of natural convection dryers is their low capacity. From our experience, as well as that of others reported in the technical literature, the surface area of the racks should not exceed that of the collectors if good efficiency is to be obtained. To increase the capacity of these dryers would require an increase in collector surface area and hence a significant increase in cost. We conclude, therefore, that these dryers should only be used within family units in rural communities.

For the more significant requirements of cooperatives or industry for instance, forced-convection dryers equipped with fans should be used to ensure proper ventilation. Fans provide a much greater airflow and are, therefore, better suited, if not indispensable, for large-capacity dryers. Another advantage of forced convection dryers is that the airflow is independent of the ambient climatic conditions and, thus, can thus be regulated more easily in most cases.

In addition, the increased airflow improves the efficiency of the solar collectors, thus the collector surface area per kilogram of product can be reduced, thereby reducing systems costs considerably.

For this reason, at the request of Opération Pêche de Mopti (a public organization for fishery development in Mali), the Laboratoire de l'énergie solaire has perfected a forced convection solar dryer for fish. This system comprises a solar collector of 14 m^2 effective area, two regulated fans, and a drying chamber of about 2 m^3 (Dicko 1985, 1986). Its load capacity is about 150 kg of fresh fish. The collector is an integral element of the roof structure. The total covered volume thus includes the drying chamber as well as the fan area and a storage area for the dried products (Fig. 4).

The first prototype was constructed at Bamako on the test site of the Laboratoire de l'énergie solaire. It consisted of a collector with single glazing and a parallel twin duct. This dryer was tested extensively for 2 years. The results of these tests were encouraging (Figs 5 and 6), but we noticed that an increasingly dense deposit of dust formed on the upper face of the absorber, which significantly reduced the efficiency of the collector over time.

Later, when the second prototype was constructed at the headquarters of Opération Pêche de Mopti, we elected to use a single duct

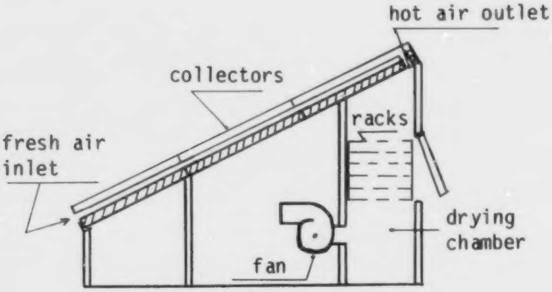


Fig. 4. Forced-convection dryer.

collector in which the air only passed below the absorber so that the upper surface was no longer susceptible to dust accumulation. This dryer is operational and is mainly used for redrying dried or smoked fish, which absorbs humidity during transport from the fishing camps to Mopti. Figure 7 shows an example of the redrying curves obtained in this dryer (Dicko 1985, 1986). In addition to fish, the forced convection dryer at Bamako has been successfully tested with other products, particularly mangoes and onions.

Although, technically, this model of dryer has given satisfactory results in various tests, it nevertheless has two major disadvantages. First, it is quite expensive because most of its components are factory-made using imported materials (steel sheet, glass wool, etc.). Second, when the drying chamber is loaded with fresh products, the dryer cannot be opened until all the products are completely dry. It

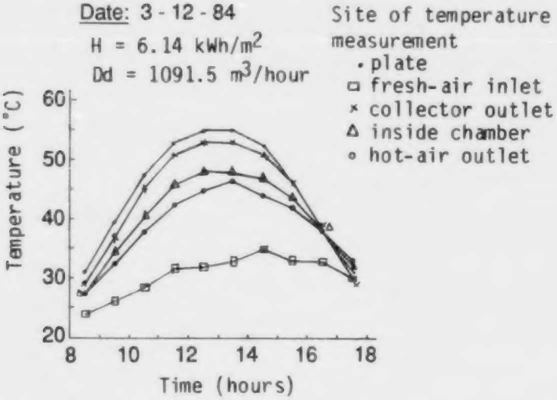


Fig. 5. Temperature readings in unloaded forced-convection dryer, 3 December 1984.

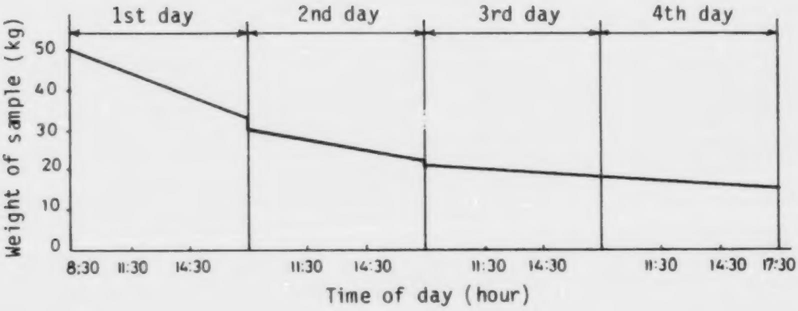


Fig. 6. Drying curve for fresh fish in forced-convection dryer.

is not, therefore, suitable when products for drying arrive daily, as is most often the case.

Clearly, from the standpoint of technoeconomic optimization, additional efforts will have to be made on this type of solar dryer if it is to enjoy general use.

Experiments in Solar Drying in the Field

The three types of solar dryer that were most successful in laboratory tests were installed in the field under the "Fish Processing Project" financed by the International Development Research Centre (IDRC), and the "Renewable Energy Project" financed by United States Agency for International Development (USAID). The three types used were the forced-convection dryer, the Taost dryer and the Greenhouse-type dryer. They were located at Bélénitiegny (San) -- two Taost dryers and two Greenhouse dryers; at Djidara (Gao) -- two Greenhouse dryers; at Mopti-ville -- one forced convection dryer; at Sensé-Daga (Mopti) -- two Taost dryers; at Batamane -- two Greenhouse dryers; and at Sélingué -- eight Taost dryers.

All these dryers were used for processing fish, a product that poses most of the problems in drying because of the abundant catch and the importance of the losses.

A socioeconomic survey was conducted after the dryers were installed. It covered four aspects: first, quantity and quality of the various types of fish sold; second, use and efficiencies of each dryer; third, parallel use and efficiency of the traditional drying method; and, fourth, quality of fish dried using solar dryers and using traditional methods.

This survey was conducted from the end of 1983 to mid-1984 but continues in Sélingué where dryers were only recently introduced. For this reason, the results obtained in Sélingué are not included here.

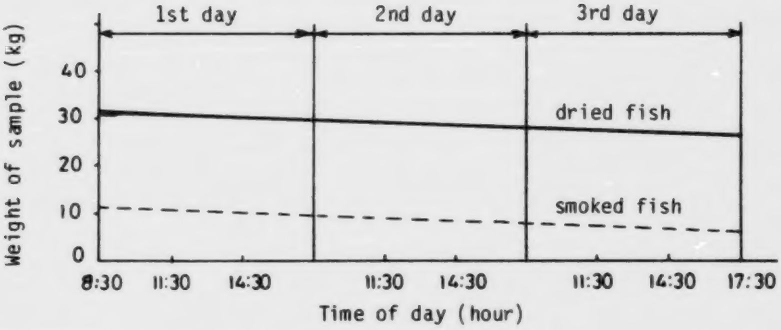


Fig. 7. Redrying curve for fish in forced-convection dryer.

The Taost-type dryers have proven to be quite weather resistant. Among the four installed at Bélénitiegny and Sensé-Daga, three are still operational. The fourth was swept away and destroyed by a wind storm in Sensé-Daga. The service life of this type of unit is, therefore, at least 3 years provided that the plastic cover is replaced regularly. During their use in the field, the following problems appeared: gusts of wind that threaten to sweep away and destroy the dryers; dust from sandstorms that can become embedded in the flesh of the fish; inadequate load capacity; and inadequately sized racks for accommodating large fish.

None of the Greenhouse dryers in any of the locations remained operational for 5 months. They lasted for 4.5 months at Bélénitiegny, 3 months at Batamané, and less than 3 months at Djidara. It should be noted that their useful life diminishes progressively as they are moved further north where winds and sun are more intense. Under the effect of the sun, the transparent polyethylene polymerizes and becomes brittle, thus it can no longer withstand the vibration caused by the wind and tears apart. Black polyethylene is much more resistant.

By covering the Greenhouse dryers with old fishing nets, the size of the vibrations can be reduced, so that tearing at the initial points of attachment can be delayed -- the fishermen themselves recommended this technique. They applied it in Bélénitiegny, and extended the useful life of the transparent plastic from 3 to 4.5 months. It should be added that the nets approved in Mali have a large-size mesh, and therefore do not shade the dryer.

The forced-convection dryer has not been used by the Opération Pêche de Mopti since the demonstration tests at the time of its installation because of the shortage of fish experienced in recent years. Because this situation is now improving, the equipment should be put back into operation to determine technical efficiencies and economic profitabilities.

Dry Products

Because of shortages of fish, low service life of the dryers, or deficiencies in the survey, we only got useful results from the Taost and Greenhouse dryers at Bélénitiegny between November 1983 and February 1984 (Table 6).

The solar dryers were well accepted by the fishermen: almost two-thirds of the fish was dried using solar dryers (Table 6). However, the fishermen continually complained about the low load capacity of the dryers. In terms of product quality, it should be noted also that solar drying had a definite advantage over traditional methods, because the wastage using the solar dryers was only 26% for the Greenhouse dryer and 30% for the Taost dryer compared with 38% using traditional drying.

This difference in efficiency between the two solar dryers can be explained by the fact the Greenhouse had only one rack whereas the Taost had five, so that the air current blowing these five racks in succession became progressively moisture laden.

According to interviews with fishermen, solar dryers have the following advantages: the drying times are shorter; the dried fish have a better aesthetic quality; and the fish have not been eaten by insects and are, therefore, heavier. However, because of the small quantity of samples produced, we were unable to determine whether solar-dried fish were better appreciated in the marketplace.

Only one redrying test was conducted using the forced-convection dryer which was loaded with both dried and smoked fish. From the standpoint of the technicians in Opération Pêche de Mopti, the test was conclusive because the water content of the fish had been lowered to a level acceptable for long-term preservation and because the fish were free from insects and developing larvae, were not brittle, and were free of the smell of oil that is characteristic of fish dried in an oil-fired oven.

Tests over a longer period would have allowed the solar dryers to be compared with the wood-fired redrying ovens that are used by Opération Pêche de Mopti in preference to oil-fired ovens.

Economic Analysis

This analysis is based on 1985 prices and applies only to the Taost and Greenhouse dryers. The quantity of fish dried annually is based on extrapolating the data for November given in Table 6: the dryers were clearly underutilized in the other months.

The economic analysis (Table 7) allows the following conclusions to be drawn. Fishermen would incur enormous losses if they used the Greenhouse dryer because of its currently short useful life. It would, however, be profitable if its useful life could be extended even to 1 year. The Taost dryer, on the other hand, is economically profitable and can pay for itself in less than 2 years.

We should caution, however, that these results were obtained during a period when the catch was relatively low. The results could be quite different in a year when the catch is normal. Under normal circumstances, each family would require three or four Greenhouse dryers or about 9 Taost dryers. However, the acquisition costs and the space required by these systems would pose insurmountable problems for fishermen, particularly those using the Taost dryers.

Future Research Program

The future research program will be structured in three main sections.

First, the results already acquired will be confirmed. In this regard, we envisage: improvement of the Greenhouse dryer to achieve better durability and much greater flexibility; reduction in cost and an increase in capacity of the Taost dryer through the use of locally available materials; better understanding of the technoeconomic effectiveness of the forced-convection dryer through an extensive series of tests at Mopti; reduction in cost of forced-convection dryers through modular design together with the use of local materials and standard components that can be manufactured by industry in serial production (efforts have already been initiated in this regard [Dicko 1986]); and a better understanding of the conditions of acceptability

Table 6. Quantities (kg) of fish dried by three solar drying methods at Bélénitiègny.

Month	**Greenhouse dryer [A]**	**Taost dryer [B]**	**Solar drying [A + B]**	**Traditional drying [C]**	**Total drying [A + B + C]**
November	123.6	73.5	197.1	107.9	305.0
December	75.7	36.2	111.9	77.1	189.0
January	34.5	13.3	47.8	32.6	80.4
February	20.5	25.7	46.2	11.2	57.4
Total	254.3 (40)[a]	148.7 (24)	403.0 (64)	228.8 (36)	631.8 (100)
Poor quality	65.7 (26)	45.3 (30)	111.0 (28)	87.7 (38)	-

[a] Values in parentheses are percentages of "total drying" for the "total" line and of dryer class for "poor quality" line.

Table 7. Economic analysis.

Parameters		Greenhouse dryer	Taost dryer
Cost of dryer (XOF)[a]		79,000	52,000
Useful life (months)		3	36
Annual depreciation (XOF)	[A]	316,000	17,333
Operating costs[b] (XOF)	[B]	31,600	1,733
Annual costs (XOF)	[C = A + B]	347,600	19,066
Annual quantity of fish dried (kg)		714.6	441
Waste products (kg)			
Actual	[D]	192.8	132.3
Equivalent from traditional drying	[E]	281.8	167.6
Product savings (kg)	[F = E - D]	89.0	35.3
Financial savings (XOF)[c]	[G]	148,630	58,951
Annual profit (XOF)	[G - C]	-198,970	39,885

[a] In 1986, 220 XOF (franc of the Communauté financière africaine) = 1.00 CAD (Canadian dollar).

[b] Estimated as 10% of depreciation.

[c] The price of dried fish in San was 1670 XOF/kg in 1985.

of dryers and their socioeconomic repercussions by introducing and monitoring an adequate number of installations in the fishing and farming communities.

Second, a better picture of the physiological characteristics of the products to be dried must be acquired. In this regard, we envisage: the completion of a drying tunnel equipped with an electric heater, adequate instrumentation, and control systems for regulating at will the temperature, humidity, and speed of the drying airflow. This facility will allow us to establish the best laboratory conditions for drying the various products.

Third, new products will be dried. In this regard, we are interested in products that have not been adequately tested, such as fruit and vegetables, or in products that have not yet been tested at all, such as tobacco and cereals. We would then be able to propose to the economic authorities not only solar dryers, but also complete procedures including possible preprocessing and storage methods.

The future research program thus defined envisages greater use of computers means for modeling and simulation.

Conclusion

Mali's climate is well suited to the practice of drying, which has been applied for time immemorial to a large number of products. Unfortunately, traditional methods incur losses that are often enormous and result in products whose hygienic quality leaves much to be desired. Research undertaken to date has facilitated the perfection of natural- and forced-convection solar dryers that are technically well adapted to drying fish, fruit, and vegetables.

Experiments with these dryers in the field have been limited and results obtained are not definitive. They have, however, emphasized some technical as well as economic deficiencies, such as low capacity, high cost, and low durability. In addition, they have demonstrated that solar dryers are well accepted within the fishing community.

In the future research program, we plan: to consolidate the results already obtained, especially by reducing costs and using local materials; to gain a better understanding of the physiological characteristics of the products to be dried; and to perfect complete procedures for products that have not been adequately studied or even studied at all.

Two broad conclusions can be made. First, the technical feasibility of solar drying has been demonstrated for some products although it remains to be demonstrated for others and, second, the socioeconomic impact of solar dryers will require further investigation before a final determination can be made.

Bibliography

Dembele, S.X. 1982. Séchage solaire de la mangue: quelques résultats. Laboratoire de l'énergie solaire, Bamako, Mali. Internal Report.

____________ 1985. Évaluation des séchoirs solaires à Bélénitiegny (San) et Djidara (Gao). Laboratoire de l'énergie solaire, Bamako, Mali. Internal Report.

Dicko, M. 1985. Solar fish drying project at Mopti. Paper presented at the International Conference on Research and Development of Renewable Energy Technologies in Africa, Mauritius, 25 March - 1 April 1985.

____________ 1986. Faisabilité technico-économique du séchage solaire au Mali. University of Perpignan, France. Doctoral thesis submitted July 1986.

Duffie, J.A., Beckman, W.A. 1980. Solar engineering of thermal processes. John Wiley and Sons, New York, NY, USA.

Traore, C.O. 1982. Les produits couramment séchés. Laboratoire de l'énergie solaire, Bamako, Mali. Internal Report.

____________ 1982. Les séchoirs à convection naturelle. Laboratoire de l'énergie solaire, Bamako, Mali. Internal Report.

POTENTIALS AND PERFORMANCE STUDIES OF SOLAR CROP DRYERS IN MAURITIUS

Y.K.L. Yu Wai Man[1]

Abstract *— A study of the potentials for the use of solar dryers as alternatives to traditional sun drying methods and as a means of supplementing artificial dryers to preserve agricultural surpluses is outlined. Evaluation of available solar energy in Mauritius shows that various crops could be solar dried in most regions throughout the year. The paper describes and discusses the results of experiments carried out on two solar dryers using crops such as maize, groundnuts, and rice. Both dryers employed forced convection, one using an upward flow draught and the other a downward flow. For the downward flow dryer, its relative performance using various energy-absorbing materials, such as basalt chippings and hardboard, is presented. Based on the results obtained, a technoeconomic evaluation made of one of the dryers revealed the various benefits that can be derived from the use of such dryer.*

Introduction

Monoculture has, in the past, been the norm in agriculture in Mauritius. However, under a recent policy of self-reliance, multicrop culture has been encouraged. Under this policy, it has been decided to release, in the first instance, 800 ha of the best arable land for the production of food crops and also, to further increase production, to encourage intense cultivation of crops in the interrow space of the 80,000 ha of sugarcane fields. The Government's Plan of Action (Mauritius 1983) calls for immediate action on at least 10 major crops, among which maize is the single most important (Table 1). All these crops must be dried to prevent spoilage during subsequent storage. Although some crops are harvested only during short, definite periods, others are harvested year-round and thus drying is a permanent need (Fig. 1).

The major landholders who will participate in the program of agricultural diversification normally use the established artificial drying process. However, the 1200 small-scale farmers who will also be called upon to contribute their share will obviously not be able to afford such an expensive process and open-air or sun-drying remains the only resort for them. However, sun-drying methods have several major constraints, not least of which is the inability to dry down to

---

[1] University of Mauritius, Réduit, Mauritius.

Table 1. Crop production objectives for 1987 in the self-reliance policy.

Crop	Production (t) Policy objective	Production (t) Present amount
Maize	15000	6000
Rice	6000	800
Onions	4300	3500
Groundnuts	2500	2000
Ginger	2000	450
Beans and Peas	1600	1100
Garlic	450	350
Turmeric	230	160
Chillies	225	50
Coffee	80	40

Crop	J	F	M	A	M	J	J	A	S	O	N	D
Maize	---					---	---	---				
Rice				---	---	---					---	---
Onions							---	---	---	---		
Groundnuts	---	---	---									
Ginger	---	---	---	---	---	---	---	---	---	---		
Beans & Peas							---	---	---	---		
Garlic						---	---	---	---			
Turmeric	---	---	---	---	---	---	---	---	---	---	---	---
Chillies	---	---	---	---	---	---	---	---	---	---	---	---

Fig. 1. Harvest times of various crops.

the safe moisture content for storage in all cases. For example, sun-dried maize will only reach a minimum of 14% moisture and must be further dried, artificially, to attain 12% moisture for storage.

This paper, therefore, outlines the potential for solar crop drying in the island and describes the development and experimental studies conducted on two solar dryers.

Availability of Solar Energy

Mauritius, a small island with an area of 1865 km^2, is located at about 20°S 57°E. The island has an equable maritime climate, but frequently suffers from cyclones in summer (November to March). Otherwise, it receives a fairly high level of solar radiation throughout the year. Meteorological data have been recorded by the Mauritius

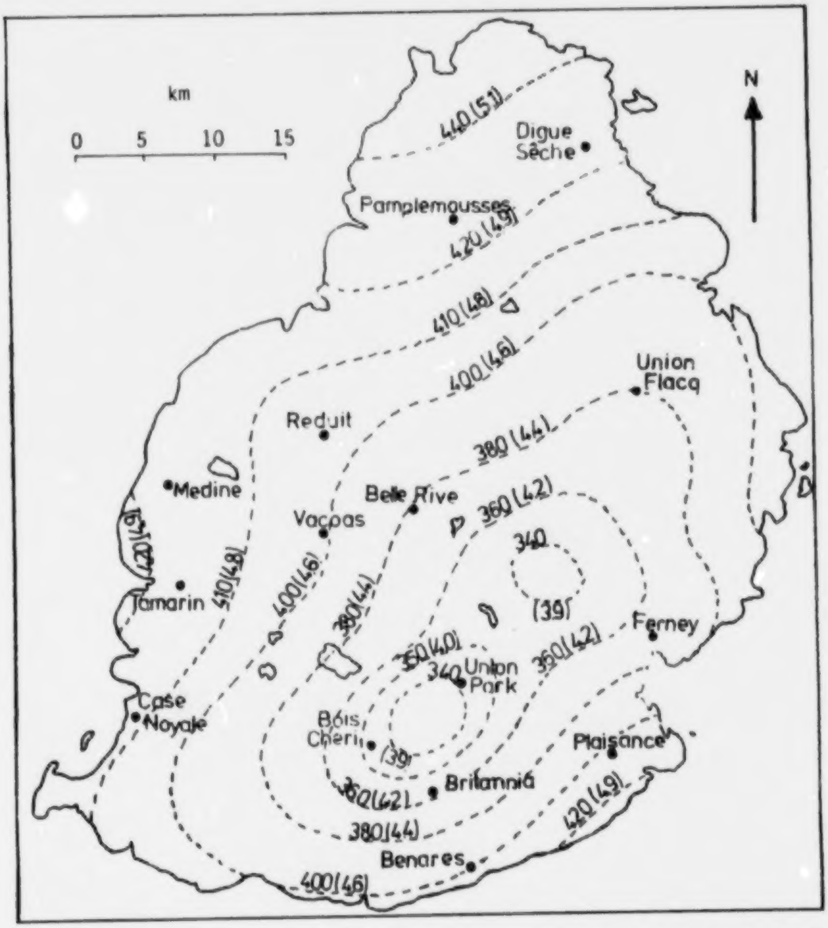

km
0
5
10
15
N
440(51)
Digue Sêche
Pamplemousses
420(49)
410(48)
400(46)
Union Flacq
Reduit
380(44)
Medine
Belle Rive
360(42)
Vacoas
340
(39)
420(49)
410(48)
400(46)
380(44)
Tamarin
Ferney
350(40)
340
Union Park
360(42)
Case Noyale
Bois Cheri
(39)
Plaisance
Britannia
360(42)
380(44)
420(49)
Benares
400(46)

Fig. 2. Daily average annual global solar radiation (in calories/cm^2 per day and in kWh/m^2 per day, parenthetical values), Mauritius.

Meteorological Services (1972) and a recent report (Vaghjee 1981) indicates that global solar radiation incident over the different parts of the island (Fig. 2) is generally 2.5-6.5 kWh/m^2 per day. Insolation varies from 5.0 to 6.2 kWh/m^2 per day in summer and from 3.2 to 3.6 kWh/m^2 per day in winter, giving a mean of 4.5 kWh/m^2 per day (Fig. 3a).

The availability of bright sunshine without interruption for the major part of the day is an important factor to take into account when evaluating the potential of solar energy for drying. The island receives about 7 hours of bright sunshine per day throughout the year. This represents an annual duration of over 2500 hours of

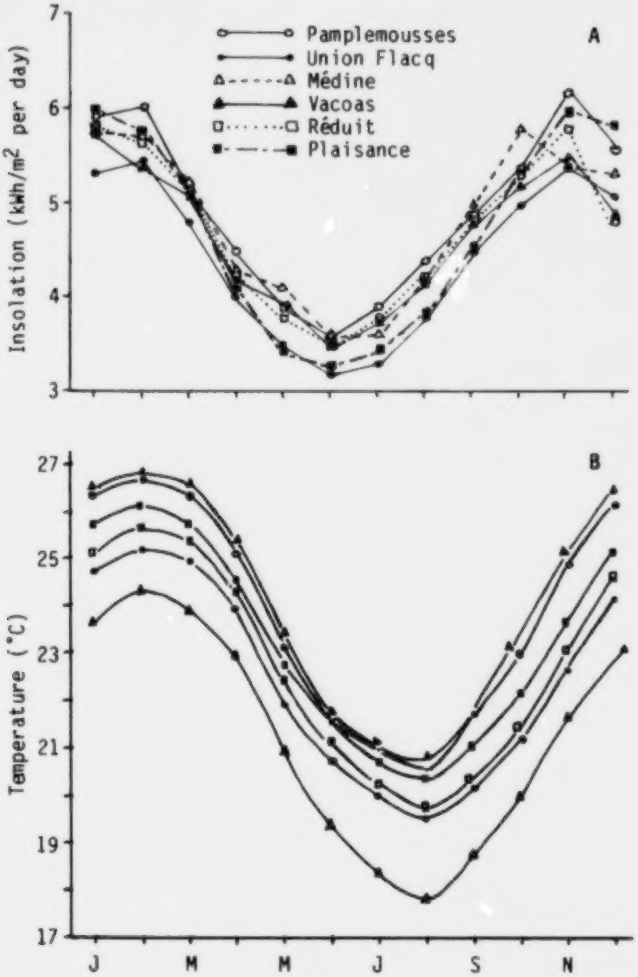


Fig. 3. Annual global solar intensities (a) and annual variation of daily mean air temperatures (b).

sunshine. Records indicate that the north of the island receives about 3300 hours with the west, south, and the Central Plateau receiving about 2600 hours and the east about 2400 hours/year. The ambient air temperature, which is related to the amount of sunshine received, varies for different regions (Fig. 3b) with maximum mean temperatures of 24-27°C in summer and minimums of 18-21°C in winter. The ambient relative humidity levels are generally high throughout the year ranging from 60% to as high as 95%. The annual rainfall is 900-2500 mm.

From these data, it is apparent that there is considerable potential for exploiting solar energy to provide the whole or part of the energy required for drying many agricultural crops. As the present bill of MUR 20 million (1 United States dollar [USD] = 14.3 Mauritius rupees [MUR]) for artificial crop drying is already too much for the island, the use of solar dryers as alternatives to artificial dryers must be investigated.

Description of Solar Dryers

Experimental studies were carried out on two solar dryers, both employing forced convection. The two dryers differ in the flow of hot air generated from the air heaters into the drying chamber.

Dryer I

Dryer I (Fig. 4) is an experimental prototype similar in design to the one developed by Excell (1980); however, different materials were used in its construction. The dryer structure was mounted on 200-mm concrete blocks, which stood on a platform of concrete 50 mm thick. Thus, the platform and concrete blocks enclosed a layer of air between the collector plate and ground to minimize heat loss to the ground.

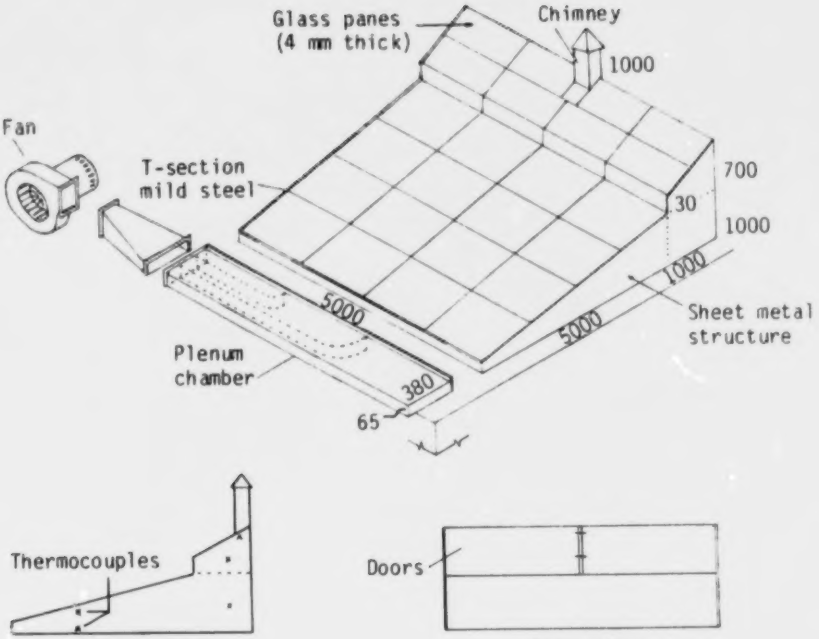
The solar absorber was made up of plain galvanized metal sheets (22 gauge) coated with matt black paint and had a collection area of 23 m^2. It was fixed and supported by a horizontal framework of mild steel bars. Sixteen clear window-glass panes (1.2 x 0.95 m x 4 mm) fitted to a mild steel structure inclined at 20° to the horizontal formed the cover of the collector system. The joint between the window frame and glass panes was sealed with metal putty. At the bottom end of the collector was the inlet vent (4.8 x 0.1 m).

The drying chamber held four trays (1.2 x 1.0 x 0.3 m) made from an iron framework with sides made of sheet metal and bottom of very fine galvanized wire mesh. Each tray could hold up to 125 kg of wet agricultural crops. Two metal doors that provided access to the chamber were insulated with bitumen-painted particle board. The chimney (0.3 x 0.26 x 1 m high) was made of sheet metal and painted black. All the sides of the dryer were made of a double layer of galvanized sheet and painted black.

Initial drying tests were carried out using natural convection, but later a forced ventilating system provided by a centrifugal fan was incorporated. The fan was powered by a 120-W, 240-V, 900-rpm motor to produce a displacement of 25 m^3 of air per minute. Two curved baffles were installed inside a plenum chamber (section of 380 x 65 mm) to provide uniform air-flow over the solar collector.

Dryer II

Dryer II, which was being used commercially on a small scale to dry fruits and potato-paste chips (chipec), was constructed of 150-mm concrete blocks on concrete foundations (Figs 5 and 6). The heat absorber, which faced north and was inclined at 20° to the horizontal, consisted of a 50-mm layer of natural basalt chippings spread over 4-mm plywood painted black (Fig. 6b). The total collector area was



Side view **Rear view**

Fig. 4. Experimental prototype dryer I (dimensions in millimetres).

$20\ m^2$. Insulation was provided by a 25-mm layer of polystyrene supported on the concrete base. The space below the concrete was filled with rock. Metal window frames, glazed with 4-mm ordinary glass, were supported by precast beams.

The drying chamber had concrete block walls and four galvanized steel doors for access to the 40 trays (Fig. 6a). Each tray was made from a wooden frame and nylon mesh that supported the crops to be dried. The trays (each measuring 610 x 1220 mm) were spaced at 100-mm intervals vertically with the lowest tray 460 mm above the chamber floor. Up to 100 kg of wet produce could be dried. Below the bottom tray was an empty space and the outlet air vent (Fig. 5b). The empty space could be filled with basalt rock for heat storage.

The plenum chamber, which was built of concrete blocks and had a slightly inclined cover made of galvanized sheet, housed a fan that provided forced ventilation. Air was forced into the space between the glass cover and solar absorber (Fig. 6b) where it was heated, and then it entered the drying chamber in a downward direction through the exposed produce in the trays. The air leaving the bottom trays was still relatively warm and was used to heat the basalt rock. At night, the heated rock kept the drying chamber warm thus preventing the formation of mould.

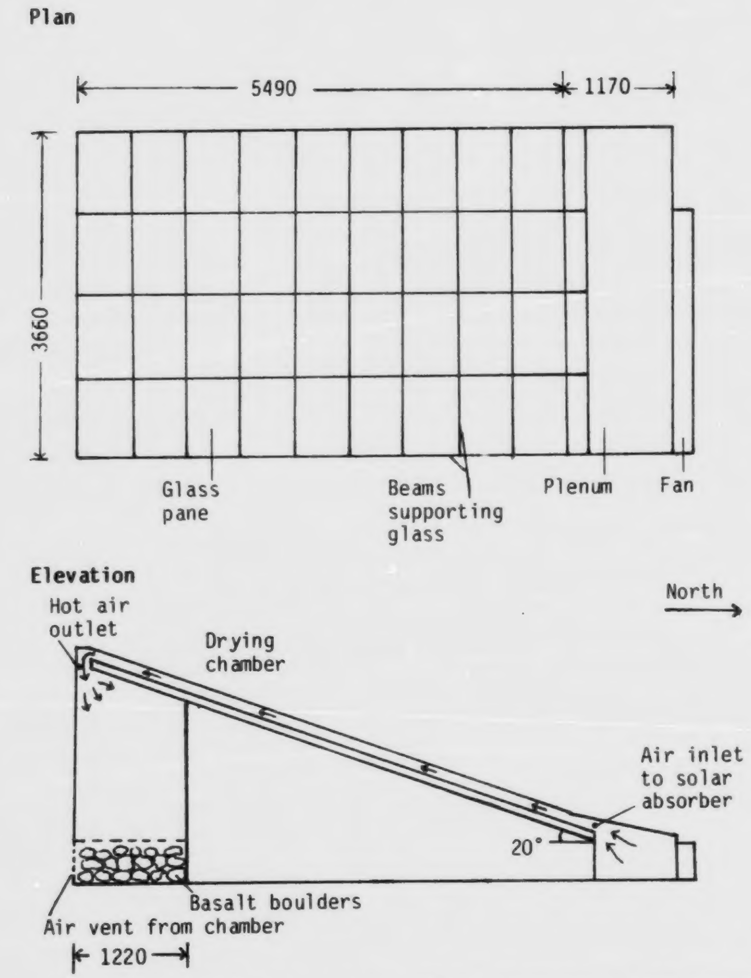

Plan
5490
1170
3660
Glass pane
Beams supporting glass
Plenum
Fan
Elevation
North
Hot air outlet
Drying chamber
Air inlet to solar absorber
20°
Basalt boulders
Air vent from chamber
1220

Fig. 5. Dryer II: plan and elevation (dimensions in millimetres).

Experimental Results and Discussion

Dryer I

In dryer I, the mean temperature rise above the ambient of the drying chamber was 22°C when unloaded (Fig. 7a). Calculated solar collector efficiency showed that it varied from a minimum of 34% to a maximum of 45%.

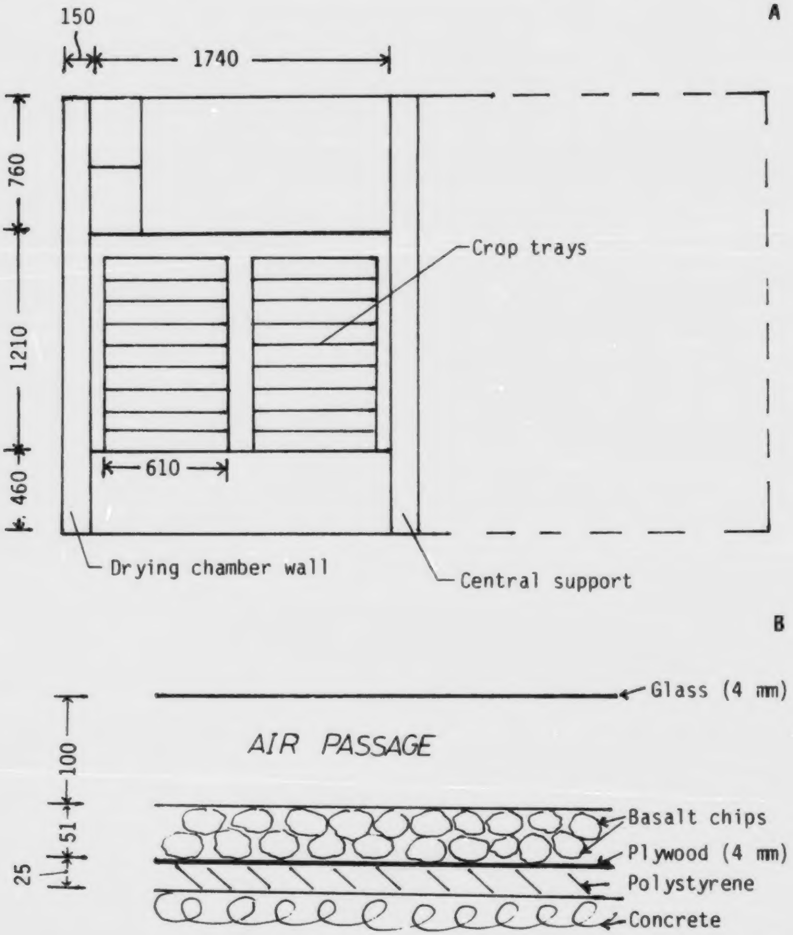

A
150
1740
760
1210
460
610
Crop trays
Drying chamber wall
Central support
B
Glass (4 mm)
AIR PASSAGE
100
51
25
Basalt chips
Plywood (4 mm)
Polystyrene
Concrete

Fig. 6. Dryer II: (a) elevation of drying chamber with one door open and (b) section of heat absorber (dimensions in millimetres).

Several drying tests on batches of maize cobs, groundnuts, and rice (100 to over 300 kg) were carried out on the dryer operating with both natural and forced convection. As would be expected, the temperature increase in the drying chamber was dependent on the available solar radiation (Fig. 8) and it was generally higher when the dryer was working under natural convection (Figs 7b and c).

For approximately the same mean solar radiation intensity, forced convection was superior to natural draught for maize (Fig. 9). Although the initial moisture contents of the maize at the start of the trials differed, the different gradients of the drying curves show

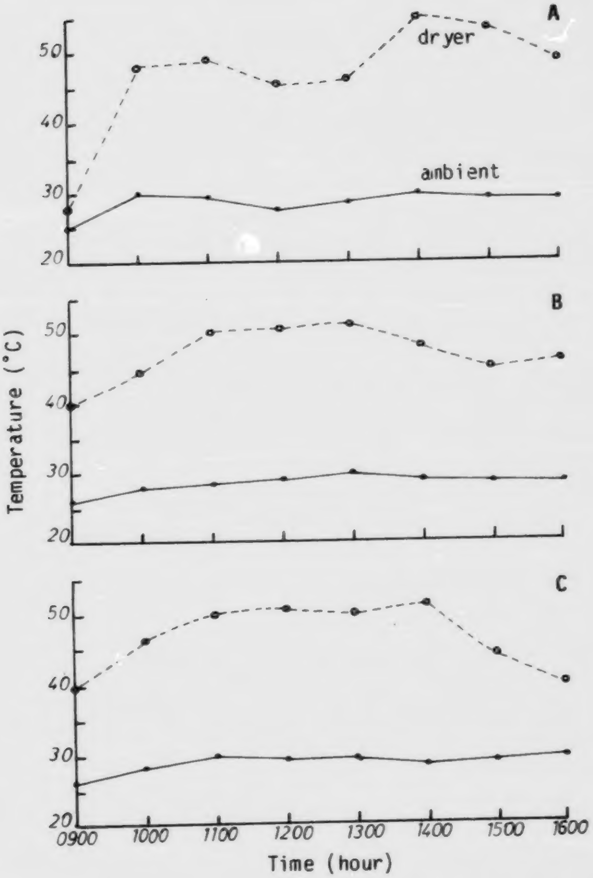


Fig. 7. Dryer I: temperature fluctuations on a typical day: unloaded (a), and loaded with maize under natural (b) and forced (c) convection.

that the rate of loss of moisture under forced convection was higher than under natural draught. For groundnuts, however, drying time was nearly the same for both operations of the dryer. This is attributable to different weights of groundnuts being dried and to different climatic conditions during the trials.

The results of various tests conducted in dryer I are summarized in Table 2. Overall efficiency of the dryer was calculated on the basis of the total energy required to remove water from a given quantity of crop to the required moisture content level, and the amount of solar radiation incident on the collector absorber. Efficiency was in the range of 11-18% for forced convection compared with 7-14% for natural convection.

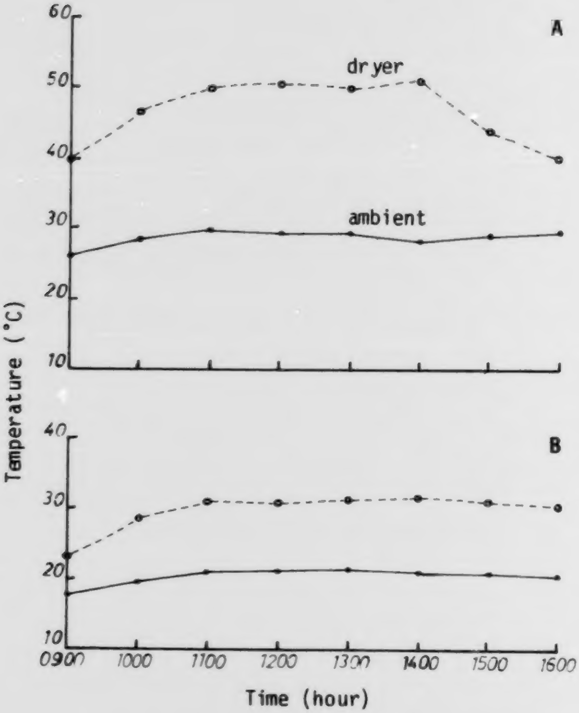


Fig. 8. Dryer I: effect of mean solar radiation intensity 625 W/m^2 (a) and 377 W/m^2 (b) on temperature.

Dryer II

Dryer II was used commercially and, because proper instrumentation was not available, an accurate determination of its performance was not possible. However, recordings of temperature inside the drying chamber and measurements of loss in weight of drying produce during tests give some useful indication of the characteristics of the dryer. With the dryer unloaded, a daily mean rise in temperature of 13°C over the ambient was obtained (Fig. 10a). Peak temperatures of 48°C were recorded inside the chamber, giving a temperature elevation of 16°C. When loaded with 20 kg of sliced mangoes, the rise in temperature during the 1st day of drying was lower (Fig. 10b) because mean solar radiation was lower. At the end of the day (at 1700 hours), the slices were turned upside down and left inside the chamber overnight with the fan turned off. During the 2nd day of drying, increases in air temperature as high as 17°C were obtained. Solar drying took 20 hours to reduce the sliced mangoes below 40% of the initial weight (Fig. 10c).

Trials with potato-paste chips showed that, generally, 2 days were required to reduce their initial weight to 50% and another

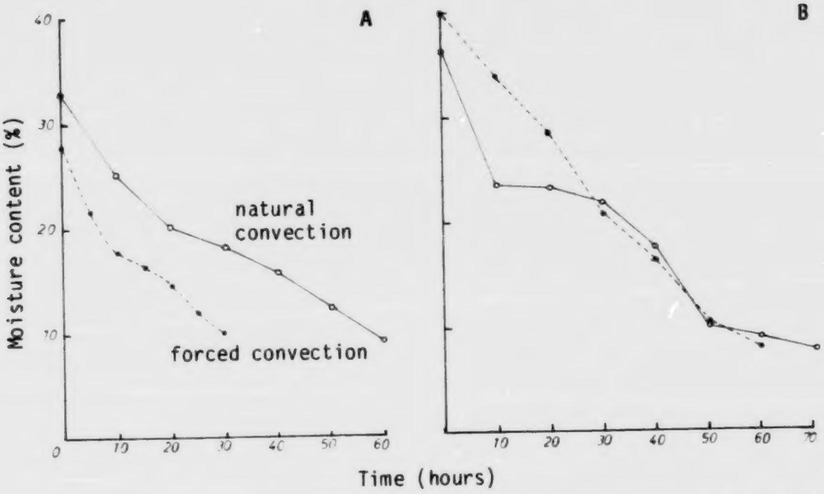


Fig. 9. Dryer I: drying curves for maize (a) and groundnuts (b) under natural and forced convection. (Note: trials of the two crops were on different days.)

2 days, depending on solar radiation, to around 10%. Because the products were left in the chamber overnight, when the relative humidity of the air increased to nearly 100%, moulds started to grow in some trays. It was apparent, therefore, that, to prevent spoilage of those products that must be dried for more than 1 day, the relative humidity of the air must be kept below 80%. This can be achieved if the dryer is kept airtight after sunset and a supplementary artificial heater used. The heater has several drawbacks that can be avoided if a heat-storage system can be incorporated in the dryer.

The downward flow dryer II lends itself very well to a heat-storage system, where the waste heat is used to warm the blackened basalt boulders placed under the drying chamber. With such a heat-storage system, the chamber temperature can be maintained throughout the night until sunrise (Fig. 11).

Effect of Different Solar Absorbing Materials on Temperature

A preliminary study of the effect of different solar absorbing materials on chamber temperatures of dryer II under no-load was conducted. A mean rise in chamber temperature of 13°C was obtained with basalt chippings when the mean solar radiation intensity was 447 W/m^2. This gave a collector efficiency of about 41%, which compared favourably with that obtained with blackened galvanized sheet in dryer I. When the basalt chippings were removed, leaving the 4-mm blackened plywood as the heat absorber, an overall mean solar radiation intensity of 326 W/m^2 resulted in an average increase in chamber temperature of 8°C, giving a calculated collector efficiency of 34%. Removal

Table 2. Summary of results of drying experiments.

Crops	Fresh (kg)	Dried (kg)	Solar heat collected (MJ)	Electricity consumed (kWh)	Dryer efficiency (%)
Natural convection					
Maize cobs	104	85	792	-	6.9
Maize cobs	78	56	715	-	8.4
Groundnuts	157	110	1218	-	10.8
Groundnuts	200	132	1352	-	14.0
Forced convection					
Rice	274	219	1408	4.8	11.4
Rice	227	194	703	2.9	13.2
Shelled maize	200	156	1008	4.8	12.1
Maize cobs	339	248	1680	4.8	15.2
Maize cobs	156	119	584	2.9	17.9
Groundnuts	327	215	2088	6.0	15.1

of the basalt chippings increased the air passage between the glass cover and the plywood by 50%.

These results suggest that basalt chippings, being cheap and easily available locally, could be used as alternatives to the more expensive galvanized iron sheet.

Economics

Dryer I was designed and constructed for experimental purposes only and, therefore, the cost of about MUR 15,000 is high. Annual operating costs depend on the period of use of the dryer and are estimated to be between MUR 2700 and 3000 for 6 and 12 months operation respectively. Working on the basis that 300 kg could be dried every 4 days, about 27 t could easily be dried in 1 year.

A cost-benefit analysis reveals that, taking the figure of MUR 400 to dry 1 t of maize in an industrial dryer, the cost of the prototype dryer could be recovered in 2.0 or 5.5 years for 12 and 6 months operation per year respectively.

Problems Related to the Development and Use of Solar Dryers

The major constraint to the development of solar technology for crop drying is the high investment required for a solar dryer. In addition, certain crops that are harvested over short periods (usually several weeks) often cannot wait to be dried. As a result, the dryer will only be used during a relatively short period. Another problem is that, in Mauritius, small-scale farmers produce a variety of crops throughout the year when climatic conditions change continuously. Thus, any dryer should be suitable for drying all the crops. Further, because of insolation and climatic variations, the dryer must be well

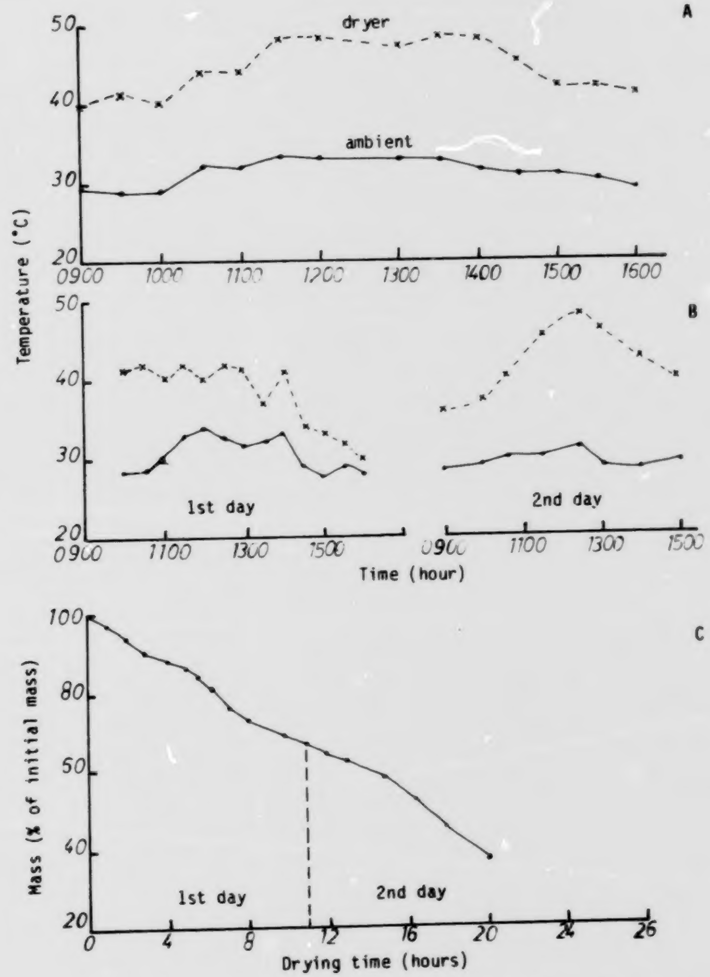


Fig. 10. Dryer II: temperature unloaded (a) and loaded with sliced fruits (b) and drying curve for sliced fruits (c). Note, drying rate was measured from 0700 to 1800 hours on 1st day and 0700 to 1600 hours on 2nd day.

insulated and airtight to prevent heat losses. It may also be necessary to incorporate a heat-storage system to avoid reabsorption of moisture at night. This is particularly important for crops with a high initial moisture content that must be dried down rapidly to avoid microbial activities that favour mould formation. Even with no mould formation, the product must be heated for 3-4 hours the following day to remove moisture absorbed overnight. This represents a waste of 3-4 hours of solar heat every day when heat storage is not available.

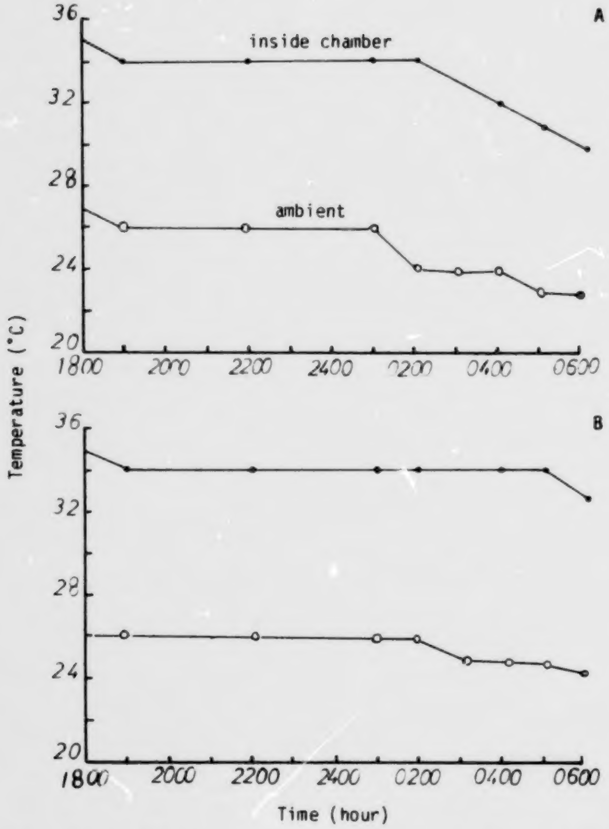


Fig. 11. Dryer II: temperature with no load without heat storage (a) and with heat storage (b).

Conclusions

An evaluation of available solar energy in Mauritius showed that a variety of crops could be solar dried in most regions throughout the year. Experimental studies conducted on two dryers have indicated, to some extent, the numerous advantages that solar drying could offer.

Results obtained with basalt chippings as a heat absorber showed their potential usefulness as alternatives to the more expensive galvanized iron sheet. The need for a heat-storage system incorporated to a dryer was found to be important for crops requiring more than 1 day of drying.

Acknowledgments -- The work carried out on dryer I was made possible by a research grant from the British Overseas Development

Administration through the Commonwealth Science Council within the framework of the African Energy Programme. I would like to express my sincere gratitude to these organizations, and also to Food Canners Ltd (Mauritius) for information relating to dryer II. Thanks are due to the Ministry of Economic Planning and Development and to the University of Mauritius for providing facilities to carry out the work. Materials contribution from the Ministry of Agriculture and the Mauritius Sugar Industry Research Institute are gratefully acknowledged.

References

Excell, R.H.B. 1980. A simple solar rice dryer: basic design theory. Sunworld, 4(6), 186-190.

Mauritius, Government of. 1983. White Paper on agricultural diversification. Government of Mauritius, Port Louis, Mauritius.

Mauritius Meteorological Services. 1972. The climate of Mauritius. Mauritius Meteorological Services, Vacoas, Mauritius.

Vaghjee, R.R. 1981. Distribution of solar radiation over Mauritius. Mauritius Meteorological Services, Vacoas, Mauritius. Technical report.

DESIGN AND TESTS OF SOLAR FOOD DRYERS IN NIGER

Yahaya Yaou, Zabeirou Radjikou, and Jean-Marc Durand[1]

Abstract *— An overview of the mission and activities of the Office national de l'énergie solaire (ONERSOL) is presented. The solar drying situation in Niger is then described with particular emphasis on meat-drying applications.*

The objectives of solar drying are specified:. they concern adequate protection against insects and dust and achieving a moisture content of 65% at the end of the 1st day of drying. A short description and critique of the various prototype dryers developed since 1980 follows. Based on simultaneous tests on chimneys of various size, a chimney of large cross-section was selected. A Sahel 50 dryer that can dry 40 kg of meat in 2 days is then described. The idea of reducing the cross-section of the air inlet on the 2nd day is also discussed. This accelerates the drying process by increasing the temperature without causing any adverse effect on the meat. The appendix describes drying kilichi and shows that solar drying can ensure good bacteriological quality of the product.

ONERSOL

The Office national de l'énergie solaire (ONERSOL) is a publicly owned national organization created on 15 May 1965. It reports to the Minister of National Education, Higher Education and Research. Its mandate is to conduct applied research on solar energy, particularly the development of various prototype equipment that operate using solar energy, and to make measurements of solar radiation. In 1975, ONERSOL's mandate was expanded to include the manufacture and marketing of solar equipment. ONERSOL has a modest budget (37 million XOF in 1986)[2], and employs a staff of 35 officers.

Current projects are improvement of the collector and solar water heater of ONERSOL; perfection of the ONERSOL-Spilling thermodynamic engine; production of electrical energy using a concentrations of photovoltaic cells; and solar drying. The solar drying division was created in 1980 after a research contract was signed between ONERSOL and the International Development Research Centre (IDRC) for a project on solar drying of onions.

---

[1] Office national de l'énergie solaire, Niamey, Niger.

[2] In 1986, 220 XOF (franc of the Communauté financière africaine) = 1.00 CAD (Canadian dollar).

Food Drying

Traditional Drying

Onions -- National production of fresh onions is very high (110,000 t in 1983). Production has increased since out-of-season cultivation was introduced. Of the total onion production, 80% is aimed at the export market, but the sales potential of dry onion abroad is unknown. Within the country, dry onion is consumed only in Niamey, where it is sold at a low price because the product is made from onions that have started to rot.

Tomatoes -- About 25,000 t of fresh tomatoes are produced annually. A tiny fraction is used directly in making sauces but, because tomatoes deteriorate rapidly, most of the overproduction throughout Niger is dried and crushed before being used in sauce preparation. There is virtually no sales problem because demand is relatively high and dried tomato can be preserved for long periods. Harvesting coincides with periods favourable to open air drying. The conditions of hygiene are acceptable.

Cucumber okra -- Production is difficult to estimate because the areas under cultivation are small and highly scattered throughout the country. The product is dried and crushed for use in making sauces.

Meat -- Animal breeding is the primary activity of the Fulani and the secondary activity of the farmers. Despite the persistent drought, this activity constitutes an important source of foreign currency because Niger exports animals and meat to neighbouring countries. Kilichi, a product that is very much appreciated locally, is made by cutting the meat into thin strips that are then dried in open air, seasoned, and redried. Kilichi is produced in towns and villages throughout the whole territory. It is, however, relatively expensive and its hygienic quality is not always satisfactory.

Prospects for Solar Drying

Onions -- Fresh onions are used, almost exclusively, in the cooking of Niger. Prospects for the sale of dry onion abroad are unknown. For this reason, solar drying of onions does not offer much potential.

Tomatoes -- Because they can be dried and preserved traditionally without loss, tomatoes do not offer any prospects for solar drying. It would not be competitive, because the harvesting and drying seasons coincide.

Meat -- Because of the volume of demand, there are prospects for solar meat drying in Niger, but their exploitation is contingent upon finding a partner interested in marketing quality dried meat for the local and export markets.

Climatic and Drying Conditions in Niger

Climatic conditions are the determining factors in solar drying. Figs 1, 2 and 3 show the variations in climatic conditions for Niamey, a town whose climatic conditions are considered representative of Niger.

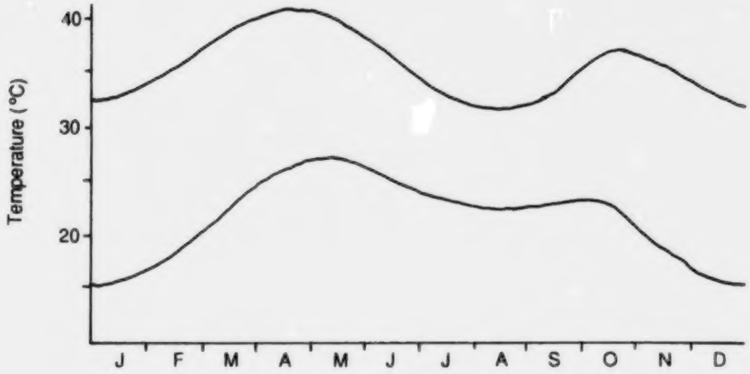


Fig. 1. Mean monthly maximum and minimum temperatures at Niamey Airport, 1951-1982.
Source: National Meteorological Service

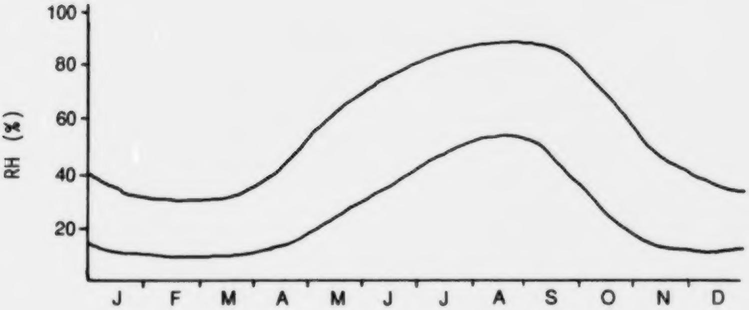


Fig. 2. Mean monthly maximum and minimum relative humidity (RH) at Niamey Airport, 1951-1982.
Source: National Meteorological Service.

Open-air drying under clear skies is possible in the humid season, from May to September, because the relative humidity drops to 55% at midday (August). Solar drying is nevertheless of interest because an increase in temperature of 10°C causes relative humidity to drop from 55 to 30% and doubles the drying potential from 0.003 to 0.006 kg water/kg dry air.

In the dry season, from October to April, drying conditions are particularly favourable. In February, the relative humidity at midday is 10% and the drying potential is 0.008 kg water/kg dry air. During this period, open-air drying is very efficient. Interest in solar drying is limited to protecting products because the heated air ensures good natural ventilation.

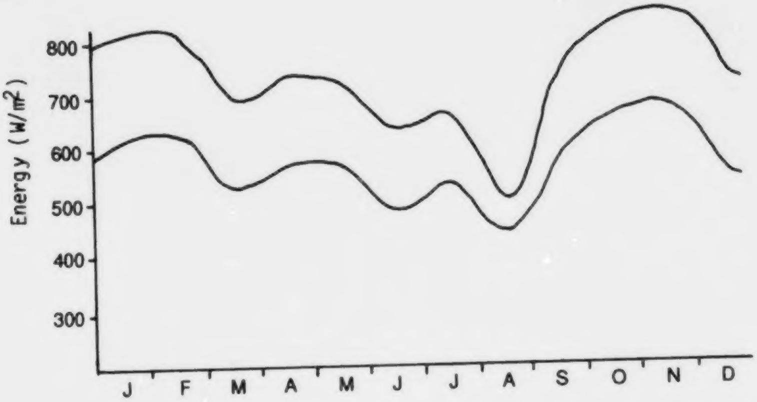


Fig. 3. Maximum and mean (0800 and 1600 hours) total solar radiation incident on a surface inclined at 13.5° (latitude of Niamey). Source: ONERSOL, Niamey, 1985.

Solar Drying Objectives

From our point of view, as well as the technical literature and the experience of ONERSOL, the objectives for the design of solar dryers have not been adequately defined. It is generally agreed that it would be desirable to have a quality dried product, a low-cost dryer, and maximum production in the minimum of time.

The objectives that we have adopted for the product are twofold: total protection against insects and predators; and a moisture content of 65% or less, or a moisure content of 1.86 kg water/kg dry matter, at the end of the 1st day of drying. For the dryer, our objectives are threefold: weather resistance; easy maintenance; and minimum cost.

The primary aim is to protect products against deterioration and contamination by insects and predators. Total drying time is not a factor that influences product quality. To ensure product quality, the moisture content must have fallen to 65% by the end of the 1st day (1700 hours TST [true solar time]) so as to prevent the development of mould and bacteria during the first night (Fournier and Themelin 1983: 110).

This value has been confirmed in a study undertaken by the Institut d'élevage et de la médecine vétérinaire du Tchad (IEMVT n.d.) on dry meat, which specifies a weight loss of 0.6 for meat with an initial moisture content of about 85%, corresponding to a moisture content of 62%. Below this moisture content, in principle, the meat is protected at least for the night. It should be noted that this criterion implies that the quantity of water that must be extracted on the 1st day may be highly variable, depending on the initial moisture content of the product. For instance, for 10 kg of fresh tomatoes having an initial moisture content of 95%, 8.6 kg of water must be extracted to achieve a final moisture content of 65%. By contrast, 10 kg of meat having an initial moisture content of 85% must lose only

5.7 kg of water. The moisture content of the product is further reduced on the 2nd day of drying to ensure good product preservation.

ONERSOL's Prototype Dryers Developed Since 1980

The first experiments on solar drying date back to 1980 when ONERSOL signed a research contract, financed by the IDRC, for a project on the drying of onions. At the time, it was thought that dry onion would sell well in Niger, but this impression was subsequently dispelled by the observations of one of the authors, following a visit to the interior of the country in July 1985.

Since 1980, five prototypes have been developed: Tower-type solar dryer (Dryer A), 1981; Aluminum solar dryer (Dryer B), 1983; Brick solar dryer (Dryer C), 1984; Wooden solar dryer (Dryer D), 1985; and the Sahel 50 solar dryer, 1986 (this dryer is discussed at length in a later section of this paper).

It was not possible to complete all of the experiments because of organizational difficulties in ONERSOL. Nevertheless, our work on each of the prototypes afforded the opportunity of coming to grips with the practical problems of operation and maintenance.

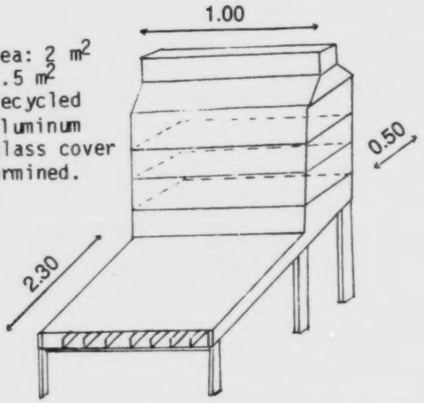
Prototype Dryers

Dryer A -- From the results of experiments on drying onions in Dryer A (Fig. 4), we were led to conclude that a design configuration in which trays are stacked in a vertical column should be definitely rejected. Natural convection is insufficent to dry the three loaded trays placed one above the other because the pressure loss reduced natural convection so that the airflow was not adequate. Because the onions were in a hot (55°C), saturated environment, they rotted.

Dryer B -- The aluminum dryer (Fig. 5) consisted of a drying chamber in which air circulated longitudinally past two racks, and where the higher rack was exposed to solar radiation through a glass. A chimney of 3 m in height ensured adequate airflow to avoid overheating of the onions. In view of its very high cost (275,000 XOF) and low capacity (only 6 kg of onions), no attempt was made to popularize this prototype. Nevertheless, it served a useful purpose in that it enabled us to define the geometry of a mixed drying chamber.

Dryer C -- Dryer C was designed to be sturdy, and was built of baked clay bricks (Fig. 6). The products are arranged in racks that rest on an aluminum drawer that is accessible from the rear. The development of the sliding system (aluminum, angle iron, girders, and grills) proved to be expensive. The glass surfaces were not removable and this made maintenance difficult. The efficiency of this dryer is summarized later.

Dryer D -- While continuing to design cement dryers, we constructed a small portable wooden dryer (Fig. 7) with family-size capacity, i.e., 6 kg of tomatoes, essentially so as to arrive at a minimum cost price. It consists of a plywood box insulated with 4 cm of wood chips and covered with plastic film. The absorber was made of black-painted galvanized steel sheet, and the racks of millet stalks. Its cost in Niamey in September 1985 was 38,000 XOF, made up of 20,000



Collector area: 2 m^2
Rack area: 1.5 m^2
Materials: recycled
aluminum
glass cover
Cost: undetermined.

Fig. 4. Dryer A, 1981.

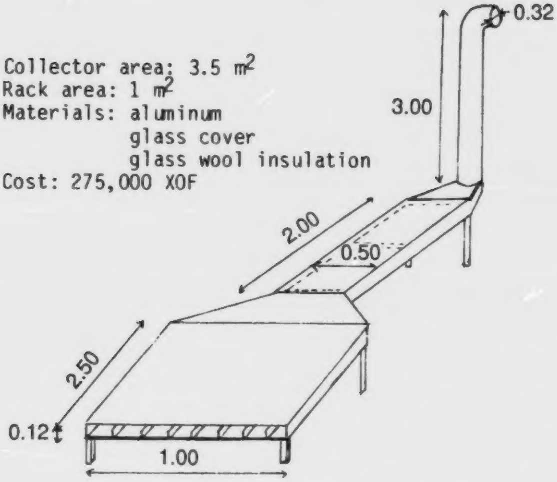
XOF for wood and 23,000 XOF for plastic film. Given the high price of plywood and the lack of replacement wood in the Sahel region, the cost of the dryer can not be reduced. Thus, it is not within the financial reach of farmers in Niger. It did, however, successfully dry 6 kg of tomatoes in 2 days. The tomatoes were put in at 1045 hours TST and, by 1430 hours TST, the moisture content had reached 65%. The following data summarize the situation at 1130 hours TST:

Outside conditions:	Inside conditions:
ambient temperature, 37°C	heater outlet temperature, 58°C
ambient relative humidity, 14%	mean airspeed at heater outlet, 0.09 m/second;
total inclined solar flux 890 W/m^2	rate of water extraction, 0.75 kg of water/hour

The EVA plastic (trade name) cover behaved well up to 60°C, but beyond that temperature it became distinctly distorted. It is not, therefore, recommended that an inlet section be installed on this particular dryer model to increase the temperature on the 2nd day of drying.

Experiments with Chimneys

During the series of tests on onion drying in 1985, the airspeeds measured over the racks were less than 0.1 m/sec, which is low compared with the values obtained in other dryers (Fournier and Themelin 1983: 117). We attempted to increase this speed by modifying the chimney. Experiments were conducted simultaneously on four different chimneys using four models of the type C dryer that otherwise were identical (Fig. 8). Three chimneys had the same cross-section but were of different heights and the fourth had a larger cross-section. The four units were loaded with the same quantity of onions (8 kg).


0.32
3.00
2.00
0.50
2.50
0.12
1.00

Collector area: 3.5 m^2
Rack area: 1 m^2
Materials: aluminum
glass cover
glass wool insulation
Cost: 275,000 XOF

Fig. 5. Dryer B, 1983.

Collector area: 5.3 m^2
Rack area: 3.5 m^2
Materials: baked clay brick
glass cover
aluminum absorber
aluminum racks
no insulation
Cost: 470,000 XOF

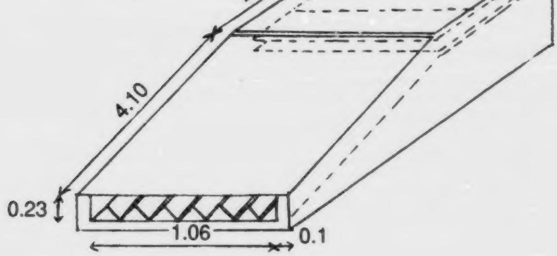

0.19
1.60
2.00
4.10
0.23
1.06
0.1

Fig. 6. Dryer C, 1984.

Collector area: 1.85 m^2
Rack area: 1.3 m^2
Materials: plywood
EVA plastic cover
galvanized steel absorber
millet stalk racks
sawdust insulation
Cost: 38,000 XOF

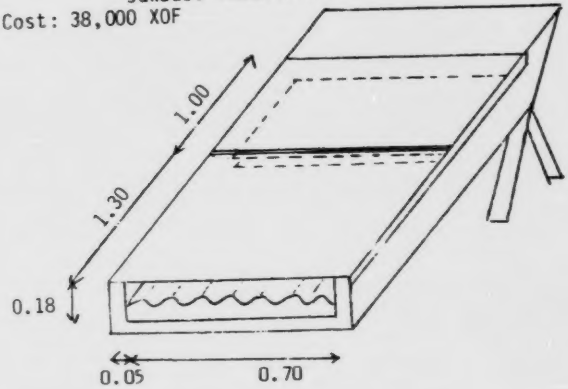


Fig. 7. Dryer D, 1985.

	Symbol				
Chimney					
Number		1	2	3	4
Height	H	1.61	2.05	2.43	2.13
Cross-section (m^2)	S	0.028	0.028	0.028	0.150
Cross-section at level of onion (m^2)	S_2	0.420 ± 0.050			
Glazed surface (m^2)					
Inclined		3.675			
Horizontal		1.666			
Surface of racks (m^2)	S_c	3.456			
Cross-section of inlet (m^2)	S_e	0.125			

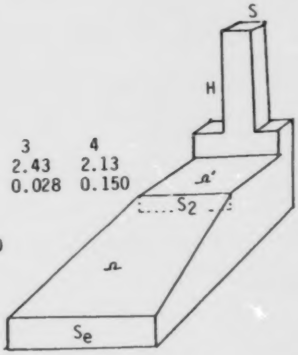


Fig. 8. Geometric characteristics of chimneys for the ONERSOL Dryer C.

Drying Conditions -- The mean drying conditions between 1000 and 1700 hours TST were: mean ambient temperature, 38°C; mean relative humidity, 47%; total inclined solar flux, 600 W/m^2.

Results -- Compared with cross-section, height of the chimney had little effect on dryer performance in terms of heater outlet temperature (Fig. 9) or mean airspeed (Fig. 10) during the 1st day of

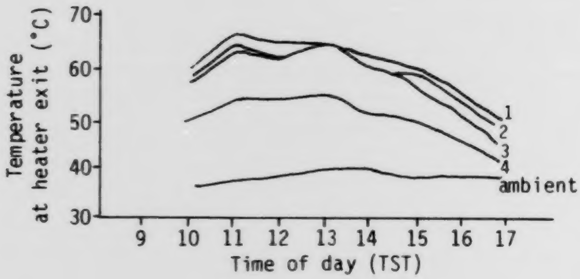


Fig. 9. Heater outlet temperature for four chimneys of various cross-sections.

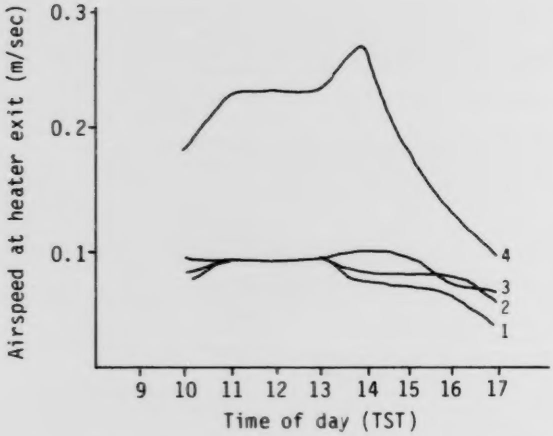


Fig. 10. Mean airspeed at heater outlet for four chimneys of various cross-sections.

drying. It follows from these observations that reducing the cross-section of the chimney inlet creates a pressure loss that cannot be compensated by increasing the chimney height from 1.61 to 2.43 m. The airspeed was doubled from 0.1 to 0.2 m/sec by using the large chimney with a cross-section of 0.15 m^2 instead of 0.028 m^2 (chimney 4 vs 1, 2, and 3). As a result, the temperature was lowered, but remained nevertheless acceptable.

Design and Testing of the Sahel 50 Dryer

Experiments on the various prototypes constructed in the past at ONERSOL led us to select a natural convection dryer with an airflow parallel to the racks. In this way, the pressure loss can be minimized, and the products can be directly exposed to solar radiation, as is strongly recommended by IEMVT (n.d.) for meat.

Observations made on Dryer C were used to design a dryer of the same type with the following characteristics: ratio of rack area to collector area at least double that of Dryer C; a larger airflow per square metre of collector area; and easier maintenance.

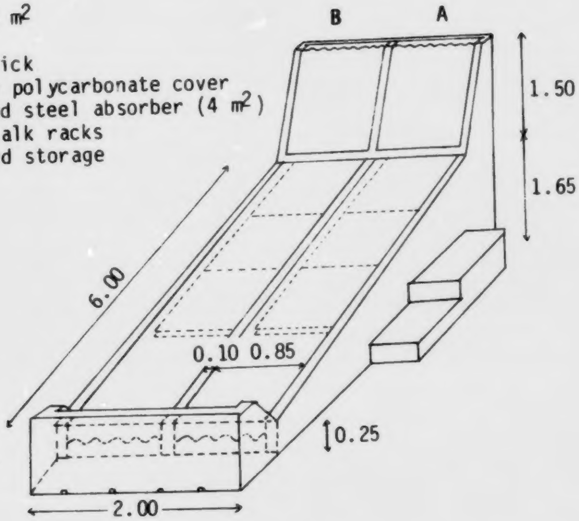
When the climatic conditions were favourable, the air heater of Dryer C proved to be too large relative to the surface area of the racks.

In the Sahel 50 dryers (Fig. 11), removing the racks is equivalent to increasing the surface area of the air heater. The load can, therefore, be adapted to climatic conditions using three possible combinations (Table 1).

The transparent surfaces are accessible from the sides to facilitate cleaning. The dryer consists of two identical units placed side by side.

The cross-section of the chimney was not reduced. The south face of the chimney was inclined at 10° to the vertical. Thus, at Niamey, with a latitude of 13.5°, the chimney casts no shadow on the dryer at the time of the summer solstice. The chimney is made from blackened steel sheet to act as the absorber of a heating chimney. The effectiveness of this device has not yet been tested. The drying chamber has the same inclination as the heater, but the slope is insufficient to cause sliding of the products on the racks. A low wall (0.6 m high) was built 1 m from the inlet section to prevent dust from entering during strong winds.

The transparent cover was made of polycarbonate honeycomb 4.5 mm



Collector area: 10.2 m^2
Rack area: 13.6 m^2
Materials: cement brick
honeycomb polycarbonate cover
galvanized steel absorber (4 m^2)
millet stalk racks
pebble bed storage
Cost: 550,000 XOF

Fig. 11. Sahel 50 dryer, 1985.

Table 1. Possible configurations and loads for Sahel 50 dryer.

Heater surface area (m^2)	Rack surface area (m^2)	Maximum load of *kilichi* (kg)
3.4	13.6	50
5.7	9.0	33
7.9	4.5	16

thick. This choice was dictated by its behaviour at high temperature, because temperatures can reach 70-90°C in the dryer when the inlet cross-section is reduced during the 2nd day of *kilichi* drying. The polycarbonate seemed suitable, because it retains its shape up to 110°C, has a good greenhouse effect, and is rigid and shock-resistant.

The polycarbonate plates had to be painted brilliant white near the supports because the local greenhouse effect strongly heated the plate and caused deformation. After cleaning the honeycomb with compressed air, the extremities were blocked with adhesive tape that can be removed to empty any water vapour that may accumulate in the long term. The cleaning was done gently to avoid scratching the plastic. The absorber was made of galvanized steel sheet painted matt black. For reasons of economy, the racks were made of millet stalks instead of metal mesh (200 XOF/m^2).

Tests Without Load

Tests were conducted on the unloaded Sahel 50 dryer to compare two types of absorber and to determine the effect of mosquito netting at the inlet.

The performance (air flow rate and temperature level) of a loaded dryer cannot be compared with that of an unloaded dryer. Nevertheless, no-load tests conducted simultaneously on the two units enabled a choice to be made between the two types of absorber.

The absorber chosen was the galvanized steel sheet painted matt black. These sheets have low thermal inertia, are easily cleaned and are affordable (1900 XOF/m^2). Under natural convection conditions, the shape of the absorbers has little influence on the performance of the collectors (Fournier and Themelin 1983:123). On the other hand, whether the air circulation is single or double flow can be important. Therefore, two types of absorber configuration were tested, each having the same flow sections. In unit B, the air circulated only under the absorber, and a layer of stagnant air was trapped between the absorber and the plastic. Unit A had air flow both above and below the absorber.

At 0900 hours TST on 25 March 1986, unit B had a superior performance: flow rate of 240 m^3/hour instead of 200 m^3/hour as in unit A and a temperature rise of 7°C instead of 6°C.

At 1100 hours TST, the polycarbonate plate of unit B became deformed. The stagnation temperature of the layer of air had become too high so that the experiment had to be terminated. We concluded that it was not possible to use the single flow configuration without overheating and damaging the polycarbonate.

The most effective protection against insects is provided by a metallic mosquito net placed at the dryer inlet. Tests were conducted simultaneously on unit A with a mosquito net and unit B without a mosquito net to verify whether the mosquito net caused too large a pressure drop. On 26 March 1986 between 1100 and 1500 hours TST, we observed that this pressure drop caused a decline in flow rate of between 275 and 240 m^3/hour and a temperature increase from 49 to 50°C. Despite the reduction in performance, which was actually quite small, it was decided to install metallic mosquito nets.

It was also decided to use pebbles for storing part of the heat of the day for use at night to create a weak air circulation and thus prevent the products being left in a saturated environment. In unit A, about 1 m^3 of ferruginous lateritic rock was placed under the first racks after the heater (Fig. 12).

We placed two metal sheets separated by a layer of air under the racks of unit B. After several days, the temperature in the centre of the pebbles stabilized at 37°C. During the night, when the outside temperature was 30°C, the inside temperature was 31°C and the airflow was not measurable. The kinetics of heat transfer to the environment were too slow to be effective, and the temperature differences were too low because thermal transfer by conduction was inadequate. The air current during the day would have to dry all the pebbles, but the pressure loss would be too great. For normal operations, this storage system is not worthwhile. To increase the pebble temperature, practically all of the inlet section would have to be blocked for several days before drying starts, and this is not always possible.

Regulation of Inlet Air

The only way to influence the temperature-airspeed relationship of a natural convection dryer is to create an additional pressure drop in the system. The simplest way is to vary the cross-section at the

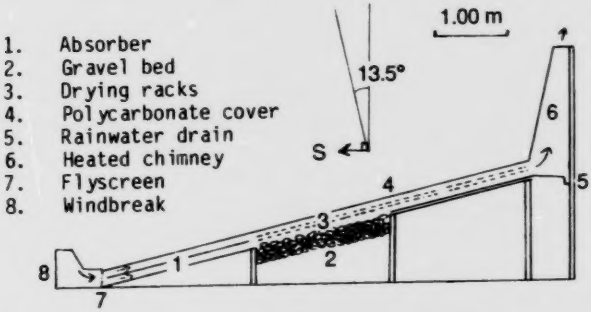


Fig. 12. SAHEL 50 Dryer, ONERSOL

heater inlet. When the heater inlet is partly closed, airspeed decreases and temperature at the heater outlet increases. In the rainy season, by partly closing the inlet section of the heater, the relative humidity at the heater outlet can be lowered to below its normal high value of 75%.

Where the relative humidity at the heater outlet is low, say between 5 and 30%, two possibilities arise, one applicable to the first phase of drying and the other to the second. During the first phase, when free water is being extracted from the product, the flow rate exerts an important influence on drying (Fournier and Themelin 1983:110). The drying power of the airflow is a function of both airspeed and temperature. The problem is to know whether reducing the inlet section can increase the drying power of the air, regardless of the fact that the airspeed affects the kinetics of drying. We denote the drying power by D. D is the volume flow rate of evaporated water, whether drying is adiabatic or isenthalpic, for an outlet relative humidity of 65%.

$$\begin{aligned} D &= m_d(x_2 - x_0) \\ &= (Vm)(S)(x_2 - x_0)/v_1 \qquad [1] \end{aligned}$$

where:

x_2, x_0 = absolute humidity at outlet and inlet respectively
m_d = dry airflow
V_m = mean speed at heater outlet
v_1 = volume of humid air containing unit mass of dry air at heater outlet
S = cross-sectional area at heater outlet.

We approached the problem by considering the real case where the inlet air temperature is 30°C and its relative humidity is 20% (month of February). Curves of constant water extraction rate were then plotted as functions of speed and temperature at the heater outlet. For a given value of D, the parameters x_2 and v_1 were obtained from a psychrometric chart to determine the relationship between speed and temperature. Across this family of curves, we then plotted points corresponding to the temperature and speed at various openings of the inlet section (Fig. 13).

At M_0, the section is fully open; at M_1, it is 60% closed; and, at M_2, the section is 90% closed. This curve was drawn using experimental data obtained from the Sahel 50 dryer. Reducing the inlet section has a stronger influence on airspeed than on temperature (Fig. 13), and therefore reduces the drying power. We conclude that, in this particular case during the first phase of drying, it is important to limit the pressure drop as much as possible.

During the second phase of drying, the bound water is evaporated. The evaporation rate is much lower than during the first phase. Moreover, the airspeed has practically no influence on the kinetics, providing it is sufficient to extract the water, because the transfer boundary has migrated inside the product. On the other hand, temperature has a very great influence. Increasing the temperature reduces the partial pressure of the water in the air, and increases

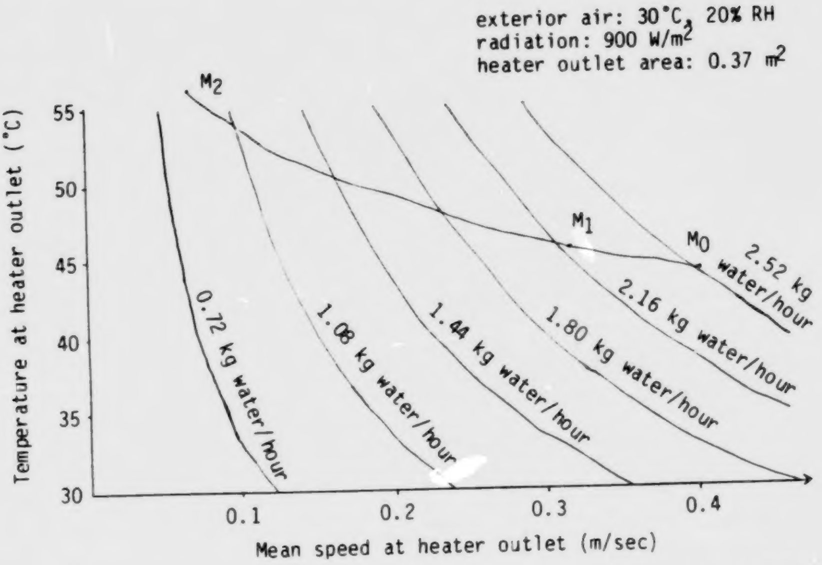


Fig. 13. Sahel 50 Dryer: operating curve (M_0 to M_2) for various inlet areas superposed on curves of constant water evacuation rates (in kg water per hour).

the saturation pressure at the interface. For this reason, during the 2nd day of meat drying (the second phase), we partially closed the inlet section while controlling the relative humidity at the outlet (moisture content 65%) to accelerate the drying process and reach a lower moisture content of the meat.

In practice, we observed that a reduction of 90% in the section was worthwhile on the morning of the 2nd day. During the day of 17 April 1986, when the section was closed to 90%, the temperature at the heater outlet increased from 56 to 66°C, whereas the increase in humidity at the dryer outlet was hardly perceptible because the evaporation rate was very low.

At the end of the day, the meat had reached a moisture content of 4.6%, and the dryer had functioned as a drying oven.

Test Under Load

To test the Sahel 50 dryer under load, we used it to dry kilichi -- the thin strips of dried seasoned meat that are prepared traditionally in Niger. Starting with 50 kg of fresh boned beef purchased from the slaughterhouses of Niamey, the butchers prepared 29 kg of usable pieces in the traditional manner (see Appendix). One unit of the Sahel 50 dryer was loaded with 18 kg of fresh strips on 16 April and the meat was dried on 16-17 April.

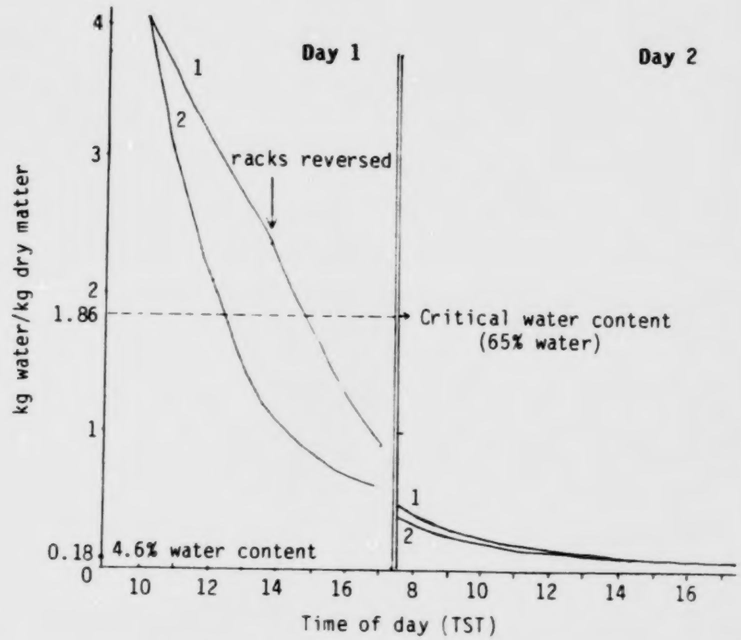


Fig. 14. Sahel 50 Dryer: kilichi drying on 16 and 17 April 1986 (initial load: 18 kg of fresh meat per unit; final load: 3.78 kg of dried meat per unit).

Because the meat was on racks that could be removed from the dryer, we could weigh the racks with the meat and were able to plot the curves of moisture content to dry base as a function of time (Fig. 14).

After 5 hours, all the meat had a moisture content below 1.8 kg of water/kg of dry matter, i.e., less than 65% moisture. The drying was, therefore, successful. On the 2nd day, the air inlet section was closed down to 90%, raising the temperature to 72°C and drying the meat to a moisture content of 7% by the end of the day. The airflow on the 2nd day was adequate (30 m^3/hour instead of 180 m^3/hour when the section is open). The relative humidity at the outlet was less than that at the chamber inlet because of the rise in temperature (Fig. 15) due to absorption of solar radiation by the higher racks. The second drying after seasoning was not studied. The seasoned strips have an initial moisture content lower than that of fresh meat (40% instead of 80% water).

Drying Conditions on the 1st Day -- Mean hourly values of the parameters between 1000 hours and 1700 hours TST were: mean ambient temperature, 43.5°C; mean relative humidity, 20%; maximum total inclined radiation, 850 W/m^2; mean total inclined radiation, 275 W/m^2; airflow, 70-180 m^3/hour for one unit; air speed past the meat, 0.2-0.4 m/sec; and mean temperature in the drying chamber, 52°C.

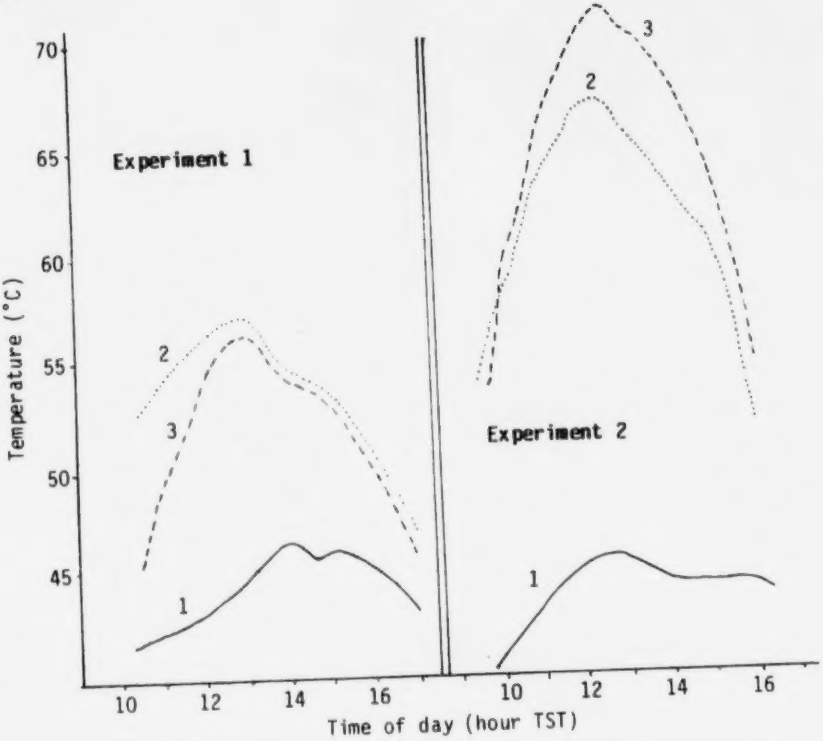


Fig. 15. Sahel 50 Dryer: kilichi drying on 16 and 17 April 1986 (1 -- Ambient temperature; 2 -- heater outlet temperature; 3 -- drying chamber outlet temperature). Experiment 1: inlet section fully open, maximum air flow rate 180 m^3/hour per unit. Experiment 2: inlet section 90% closed, maximum airflow 30 m^3/hour per unit.

Performance Efficiency

To measure the performance of the Sahel 50 Dryer, readings were taken during the 1st hour of drying kilichi when the rate of water vapour extraction is a maximum. From measurements of temperature and airspeed, we were able to determine various parameters defining the state of the humid air at three points in and around the dryer at 1030 hours TST (Table 2).

Drying Efficiency -- Dryer efficiency (η_d) can be defined as the fraction of incident solar power that is used in vaporization.

$$m_d = (V \times A)/\nu_2$$
$$= (0.28 \times 0.185)/0.948 = 0.0546 \text{ kg dry air/sec} \qquad [2]$$

$$m_w = m_d(x_3 - x_2) = m_d(x_3 - x_1)$$
$$= 0.0546(0.0257 - 0.0185)$$
$$= 4 \times 10^{-4} \text{ kg water/sec} \qquad [3]$$

$$\eta_d = (m_h \times L_v)/Rg \times A)$$
$$= (4 \times 10^{-4} \times 2258.3 \times 10^3)/(752 \times 5.1) = 0.23 \qquad [4]$$

where:

A = collector area (m^2)
m_d = mass flow rate of dry air (kg dry air/sec)
m_w = mass flow rate of water in dry air (kg water/sec)
L_v = heat of vaporization per unit mass
V = mean air velocity (m/sec)
Rg = global incident radiation (W/m^2)
x_n = absolute humidity of air -- x_1, ambient; x_2, at heater outlet; and x_3, at drying chamber outlet (kg water/kg dry air).

The value of 0.23 is quite acceptable, because it was obtained at the beginning of drying, and compares with values given in the literature (Fournier and Themelin 1983:110).

Collector Efficiency -- Collector efficiency (η_c) can be defined as the ratio of the power provided by the heater to the incident power.

Table 2. Performance of the Sahel 50 dryer loaded with 18 kg of fresh meat per unit.

Parameters	Ambient (1)	Heater outlet (2)	Drying chamber outlet (3)
Dry temperature (°C)	41.5	52.0	45.9
Humid temperature (°C)	28.0	-	32.5
Absolute humidity (kg water/kg dry air)	0.0185	0.0185	0.0257
Relative humidity (%)	37	22	45
Enthalpy per unit mass (kcal/kg dry air)	21.8	23.9	27.0
Volume relative to dry air (m^3 humid air/kg dry air)	-	0.948	-
Mean air speed (m/sec)	-	0.28	-

$$\eta_c = [m_d(H_3 - H_2)]/[Rg \times A]$$
$$= [0.0546(23.9 - 21.8) \times 4185]/[752 \times 1.8] = 0.35 \quad [5]$$

where:

H_2 = enthalpy per unit mass of air at heater inlet
H_3 = enthalpy per unit mass of air at heater outlet.

The value of 0.35 is of the right order for a collector operating under conditions of natural convection.

Adiabatic Efficiency of Drying Chamber (η_x) -- The absolute humidity at saturation for isenthalpic drying was determined from the psychrometric chart.

$$x_s = 0.0395 \text{ kg water/kg dry air}$$
$$\eta_x = (x_3 - x_2)/(x_5 - x_2)$$
$$= (0.0257 - 0.0185)/(0.0395 - 0.0185) = 0.34 \quad [6]$$

where:

x_s = absolute humidity at saturation (kg water/kg dry air).

Because actual drying is not adiabatic, the value of 0.34 is low, which implies that the dryer could have taken a greater load. This is confirmed by the fact that the relative humidity at the outlet was 45%, and that the moisture content of the meat had dropped to 65%, the criterion that we had initially specified, well before 1700 hours TST.

Based on these calculations, it is clear that the Sahel 50 Dryer can dry 40 kg of kilichi in 2 days under the hot season conditions of Niamey.

Dryer Costs

The cost of the dryer is high (Table 3) because all the materials used were imported from France or Nigeria. In particular, the polycarbonate was shipped by air, which increased its cost. In fact, the polycarbonate accounted for 35% of the total cost. In this context, we have no information on whether substitute materials could be found. This implies that the cost of construction of a dryer built with durable materials and unbreakable transparent surfaces would inevitably be high (40,000 XOF/m^2 of installed rack).

At such a price, we envisage only one potential purchaser in Niger, the Société nigérienne d'exploitation des ressources animales (SONERAN), with whom discussions have already been held.

Conclusion

In the socioeconomic and climatic context of drying in Niger, it appears that meat is the only product for which solar drying could find an application.

The experience gained by ONERSOL on solar drying in the laboratory has resulted in the development of a reliable dryer with a

Table 3. Cost of Sahel 50 Dryer, Niamey, March 1986.

Item	Quantity	Unit price (XOF)	Total price (XOF)[a]
Cement blocks (0.2 x 0.1 x 0.4 m)	500	180	90 000
Transparent polycarbonate plates (2.1 x 3 m)	2	96 000	192 000
Bags of cement (50 kg)	20	2 900	58 000
Galvanized steel sheets (2 x 0.85 m)	12	3 100	37 200
Rafters (0.04 x 0.04 x 5 m)	2	5 500	11 000
Reinforcing iron (6 mm)	1	800	800
Reinforcing iron (8 mm)	1	1 600	1 600
Load of sand	1	15 000	15 000
Wood strips (5 mm)	30	400	12 000
Plank (30 mm)	1	6 500	6 500
Matt black paint (0.7 L)	2	2 300	4 600
White paint (0.16 L)	1	1 295	1 295
Solvent (L)	1	1 770	1 770
Adhesive tape (roll)	1	1 505	1 505
Masking tape (roll)	1	1 220	1 220
Wire-strainer (5 m)	2	1 255	2 510
Steel hooks (pairs)	2	495	990
Fine string (50 m)	1	780	780
PVC pipe (m)	15	106	1 590
Metallic mosquito net (0.6 x 1 m)	1	1 300	1 300
Woven millet stalks	10	250	2 500
100 steel wire-nails (40 mm)	2	470	940
1 kg bulk wire-nails	1	1 000	1 000
Labour for brickwork[c]			107 570
Total			549 550

[a] List based on materials used in construction of prototype.

[b] In 1986, 220 XOF (franc of the Communauté financière africaine) = 1.00 CAD (Canadian dollar).

[c] ONERSOL provided all tools required for construction of prototype for a 1-week period involving two workers.

capacity of 40 kg of fresh meat. Despite its high cost (550,000 XOF), the Sahel 50 Dryer has demonstrated its ability to produce dry meat having good bacteriological qualities.

ONERSOL should now shift its emphasis to introducing experimental dryers in the user environment, provided that partners interested in the marketing of quality dried meat and sources of financing could be found.

Research prospects

All the dryers developed to date by ONERSOL were constructed with materials imported from Europe or Nigeria, which explains their high cost. No dryers have been installed and tested in the rural community. For this reason, research from now on must be directed to three points:

- Study and use of local materials in the construction of dryers;
- Development of methodologies for the diffusion of solar dryer technology and reliable systems throughout the rural community; and
- Identification of solar drying needs.

References

Fournier, A., and Themelin, A. 1983. Expérimentation des modèles Seresol et MS-003. Paper presented at the workshop Séchage solaire et développement rural, Bordeaux, 8 au 20 mai 1983. Groupe de recherche et d'échanges technologiques, Paris, France.

IEMVT (Institut d'élevage et de médecine vétérinaire du Tchad). n.d. Études bactériologiques et mycologiques des viandes séchées dans les conditions africaines. IEMVT, N'djamena, Chad.

Appendix: Drying of *Kilichi*

Preparation of *Kilichi*

Because the cutting technique for *kilichi* requires experience, the meat is prepared by butchers. They start with fresh boned beef from which they remove the fat and the sinews, keeping only long scraps of muscle. Then each scrap is unrolled using a special cutting technique that follows the grain. Thin strips of a few decimetres square and about 5 mm thick are obtained.

These thin strips are spread on racks made of millet stalks and left to dry until the following evening. Every few hours, the strips must be turned so as to avoid sticking to the millet stalks. The dried strips are then dipped into a sauce with a base of groundnut oilcake and peppers. For commercial reasons, the exact composition of

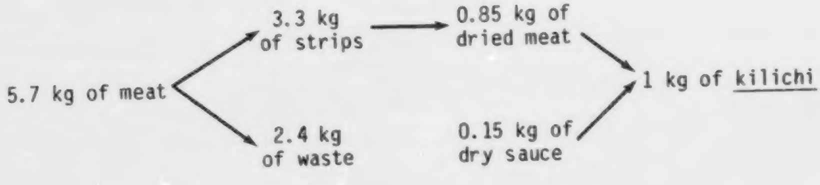


Fig. 16. Production components of *kilichi*.

this sauce is kept a closely guarded secret by the butchers. The strips absorb the sauce, become soft and are left to dry again for 2 days. Kilichi is eaten dry and is never rehydrated.

Cost of Kilichi

Because preparation of kilichi involves considerable labour and loss of the original weight of meat (removal of fat and sinews), kilichi is expensive -- but much appreciated. The components of producing 1 kg of kilichi are shown in Fig. 16. Clearly 1 kg of kilichi has the equivalent nutritive value of 3.3 kg of prime quality meat, to which has been added about 0.1 kg of groundnut paste.

Because the cost of labour in meat cutting and sauce preparation was about half that of the meat (1935 vs 3990 XOF), the final cost of the kilichi was 1.5 times more than the fresh meat -- however, it will keep for several months.

Bacteriological Quality of Kilichi

The bacteriological quality of kilichi is not always good because of contamination by insects and the low rate of drying, which allows moulds to develop. Some kilichi are known to provoke diarrhea.

To demonstrate that the solar dryer could improve the quality of the final product, tests on solar drying of kilichi were conducted in the Type C dryer between 12 and 15 November 1985. Two batches of meat were prepared by a butcher on the premises of ONERSOL: one batch was dried in the Type C dryer and the other was dried in open air. Preparation of the two batches was strictly the same except that the meat left to dry in the open air was wrapped in paper and stored in cardboard boxes overnight.

Cutting of the meat started at 0900 hours on 12 November and the first drying phase started at 1245 hours. The next day, at 1700 hours, the dried strips were gathered for seasoning, which started at 0900 hours on 14 November. Seasoning took about 2 hours so that the second drying phase started at 1100 hours. Drying was completed by 1700 hours on 15 November when the kilichi was collected.

On the 1st day, between 1245 and 1700 hours, the following conditions prevailed: mean ambient temperature, 32°C; mean ambient relative humidity, 30%; outside wind speed, 1-2 m/sec; mean temperature at heater outlet, 50°C; mean total inclined radiation; 730 W/m^2; and mean air speed past dryer trays, 0.05 m/sec.

Results -- Bacteriological analysis showed that solar-dried kilichi is of higher quality than traditional kilichi, which contained coliform and streptococci. We were unable to determine when contamination and proliferation occurred.

SOLAR ENERGY FOR CROP DRYING IN DEVELOPING COUNTRIES

E.A. Arinze[1]

Abstract -- *This paper discusses solar energy availability (with data for typical tropical locations) and applications of solar energy in agricultural production. Various methods are discussed for improving the traditional methods of sun-drying crops and commodities in developing countries by developing and introducing appropriate solar-drying techniques. In particular, the construction and performance of some controlled solar energy crop dryers developed in Nigeria are presented. Experimental data on solar energy absorption characteristics of some agricultural products are also presented.*

Introduction

Petroleum energy now supplies most of the energy for production in agriculture and industry. As the conventional petroleum fuels become scarce and expensive, the use of these high energy-content fuels in low-temperature stationary uses, such as environmental temperature and humidity control, crop drying, water heating, and irrigation must be restricted. Energy for all these can be supplied by solar energy. Solar energy technology and research are developing fast and much of the technology needed for these applications in industry and agriculture is already available.

In most developing countries, there is increased emphasis on rural development and this undoubtedly will require a phenomenal increase in the use of energy in some form in rural areas. A distinct departure must be made from the age-old techniques of exclusively using manual and animal labour, animal wastes, and firewood or charcoal as the main sources of energy. Past experience has shown that such methods are highly regressive in human as well as environmental terms. The increased use of renewable energy sources -- solar energy in its various forms -- should, therefore, be encouraged in developing countries, especially for agricultural production.

This paper presents a general outline on solar energy availability with emphasis on a typical developing tropical location (Nigeria) and other relevant climatological parameters in crop drying. Various methods of improving the traditional methods of sun-drying crops in developing countries by the development and introduction of appropriate solar crop-drying techniques are discussed. In particular, the paper describes the construction and performance of some controlled natural- and forced-convection solar energy crop dryers fabricated and tested at the Department of Agricultural Engineering of Ahmadu Bello University in Zaria, Nigeria. Useful experimental data on solar energy absorption characteristics of some agricultural products are also presented.

---

[1] Department of Agricultural Engineering, Faculty of Engineering, Ahmadu Bello University, Zaria, Nigeria.

Solar Energy Availability and Other Climatological Parameters

At present, the mean intensity of normal solar radiation (solar constant) outside the earth's atmosphere is 1353 W/m^2. As this radiation passes through the atmosphere, it is partly scattered, reflected, and absorbed by the atmospheric particles so that only a portion reaches the surface of the earth. The total solar radiation reaching the earth's surface has both direct (beam) and diffuse components.

The available total solar radiation on the earth's surface is intermittent and seasonal in nature. Generally, sloping the collecting surface toward the south (in the northern hemisphere) at the latitude angle will reduce the seasonal variation and lead to maximum total annual collection.

The most important factors that determine the amount of solar radiation reaching the earth's surface are:

- Composition of atmosphere;
- Depth of the atmosphere (air mass) that the radiation must pass through before reaching the surface;
- Time of day or solar hour angle -- maximum collection occurs at solar noon;
- Latitude of the location;
- Earth's tilt and rotation that determine the seasonal and daily variation in the amount of solar energy; and
- Tilt angle of the surface to the horizontal.

Figure 1 shows the daily average of total horizontal solar radiation (on a monthly basis) for two typical tropical locations (Zaria and Kano, latitudes 11°N and 12°N, respectively) in northern Nigeria. Seasonal variations in solar energy availability is slight in such tropical locations.

The annual available total horizontal solar radiation in Nigeria determined from mean annual sunshine hours (Arinze and Obi 1984b), varies from 5000 MJ/m^2, or 45% of the maximum possible value outside the earth's atmosphere, in the humid Niger Delta to over 9400 MJ/m^2, or 70%, in the extreme northeast of Nigeria (Fig. 2). Generally, January to April are the months with greatest solar energy availability and July to September have the lowest availability: this period is also the wettest.

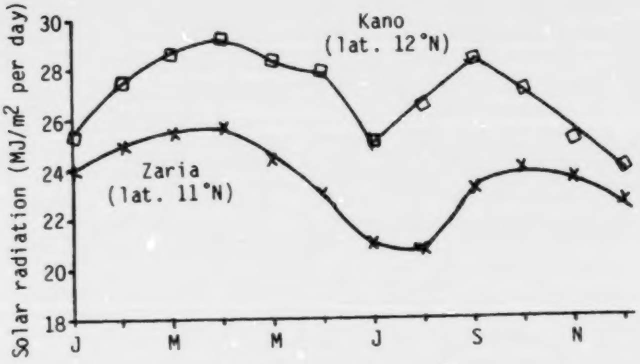


Fig. 1. Total horizontal solar radiation (daily average) for two tropical locations in Nigeria.

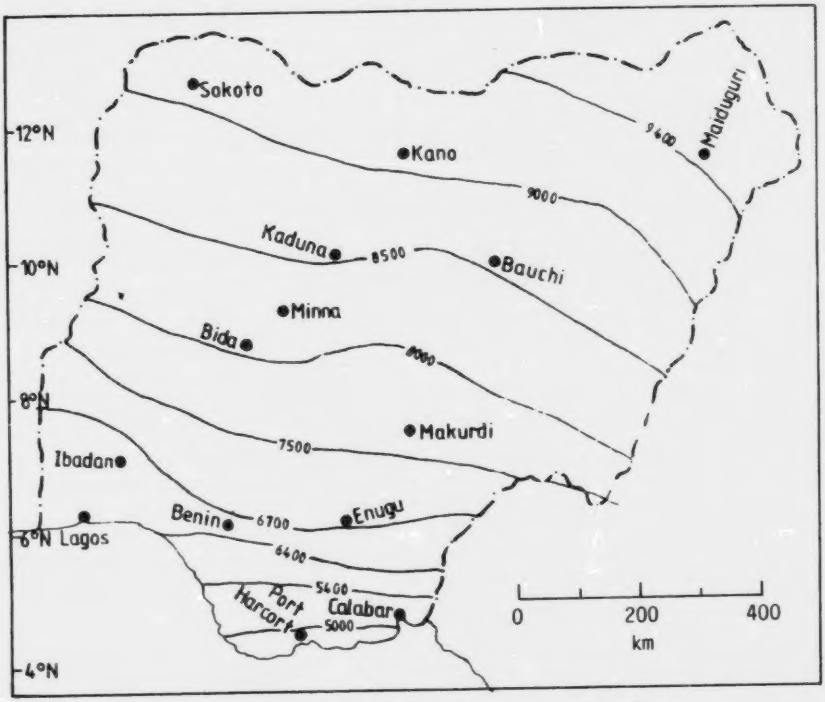

Sokoto
Kano
Maiduguri
9400
9000
Kaduna
8500
Bauchi
Minna
Bida
8000
Makurdi
7500
Ibadan
Benin
6700
Enugu
Lagos
6400
5400
Port Harcourt
Calabar
5000
12°N
10°N
8°N
6°N
4°N
0
200
400
km

Fig. 2. Mean annual solar map of Nigeria (MJ/m^2).

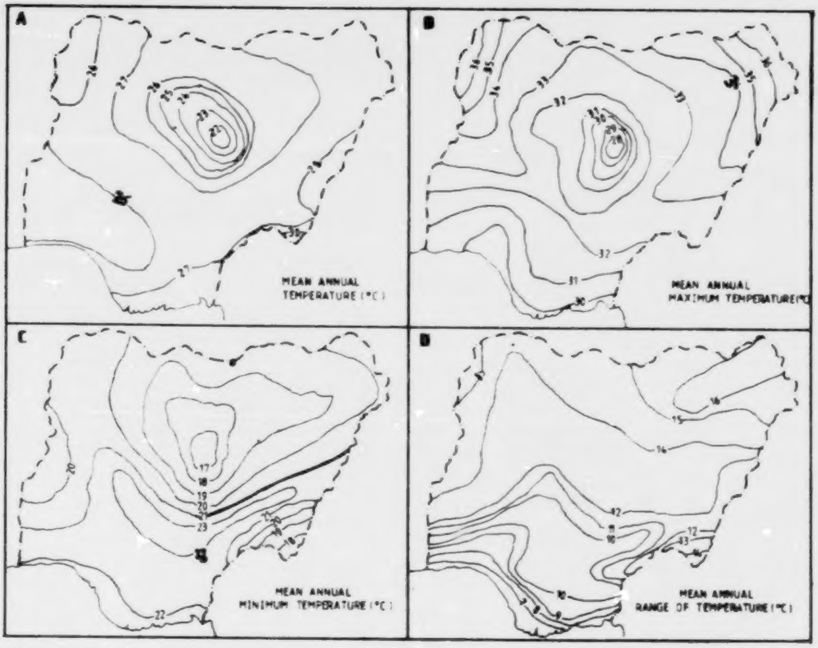

A
MEAN ANNUAL TEMPERATURE (°C)
B
32
31
30
MEAN ANNUAL MAXIMUM TEMPERATURE(°C)
C
17
18
19
20
23
22
MEAN ANNUAL MINIMUM TEMPERATURE (°C)
D
16
15
14
12
10
MEAN ANNUAL RANGE OF TEMPERATURE (°C)

Fig. 3. Outdoor temperatures (°C) for Nigeria: mean annual (A), mean annual maximum (B), minimum (C), and range (D).

Nigeria is within the tropics, and it experiences high temperatures all the year round. The mean for most stations in Nigeria is about 27°C. As with solar radiation, seasonal and latitudinal variations affect the extremes and the diurnal and seasonal ranges of temperature. The highest air temperatures are normally in March and April with minimum temperatures in the north usually in December and January, during harmattan weather, and during the rainy season in July and August in the south. Mean maximum temperatures increase from 32.2°C at the coast in the south to 40.6°C in the extreme north (Fig. 3). Mean minimum temperatures, by contrast, decrease northward with a lowest mean of 21.1°C on the coast to less than 12.8°C in the north due to the effects of continentality.

Relative humidity (RH) varies considerably both in space and between seasons. In the southern, coastal, region, June to October have monthly means over 90% but, in the north during January to April, mean values vary from 30% at dawn to 10% in the afternoon. This is characteristic of harmattan season when the dry and dust-laden northeast trade winds are blowing from the Sahara under cloudless but dusty conditions. Generally, the rainfall decreases both in duration and amount from the south coast to the interior. The coastal areas receive over 4000 mm of rain spread over 8-10 months whereas the extreme north receives less than 250 mm spread over 3-4 months.

The climate of Nigeria represents a microcosm of the climate of West Africa. The climate fluctuations in Nigeria and the rest of West Africa are not local occurrences; rather they form part of global climatic patterns.

Crop Drying Techniques

The land constraints (such as intercropping and two or more crops per year), harvesting losses, early maturing hybrids, timing of harvesting operations with respect to the field conditions (for example, groundnut must be harvested when the soil is sufficiently wet), and other factors have made it necessary to dry most crops mechanically after harvest. Harvested agricultural products must be stored dry (12-14% moisture content, wet basis) to prevent attack and destruction by microorganisms and fungi and self-heating of the products. At some stages of food preparation, drying is also necessary.

Artificial dryers are commonly used in many developed and highly industrialized countries because labour costs are high, climates unfavourable, throughputs are high, and high quality standards must be maintained. The sources of energy for these dryers are mainly electricity, gas, oil, or solid fuels. They are generally capital intensive and are not suitable for the small-scale farmers or for the majority of agroindustries in African or developing countries. Because of their size and complexity, they are incompatible with the requirements of a farmer with relatively small quantities of crops to be dried for short seasons throughout the year.

Drying with the sun's energy is an effective alternative, in whole or in part, to artificial drying although it is not capable of comparable throughput. Comparatively unskilled labour can be used to construct, operate, and maintain solar dryers using materials that are readily and cheaply available in rural areas.

Sun Drying

In several developing countries, sun drying of harvested crops is the general practice and the sun is the source of energy for drying. Generally, sun drying applies to spreading the crop in the sun on a suitable surface (such as roadsides and mats), hanging crops from the eaves of a building, trees, etc., and drying on the stalk by standing in stooks or bundles.

Although sun drying requires little capital or expertise, it has many limitations and problems. Loss of moisture is usually intermittent and irregular, and the rate of drying is generally low, thus increasing the risk of spoilage during the drying process. The final moisture content of the dried product can be high because of low air temperatures and high relative humidities: this can result in crop spoilage during subsequent storage. Contamination by dust; infestation by insects and rodents; theft or damage by birds, animals, or humans; the need for relatively large areas of land or surfaces to spread crops; and the need to move crops under cover in the event of rain are also problems associated with sun drying. However, it is still, by far, the most widely practiced agricultural processing operation: in Nigeria, over 80% of harvested agricultural products are sun dried.

Solar Crop Drying

Solar crop drying also relies on the sun as its major source of energy. However, it differs from sun drying in that a simple structure, such as a flat-plate solar collector, is used to enhance the effect of insolation and minimize loss of the collected sun energy to the surroundings. Solar drying is a good alternative to sun drying, especially for farmers in developing countries. In comparison with sun drying, solar dryers can generate higher air temperatures and consequently lower air relative humidities, both of which are conducive to improved drying rates and lower final moisture contents of the dried product. This advantage reduces the risk of spoilage both during the actual drying process and in storage. The higher temperatures attainable are also a deterrent to insect and microbial infestation, and protection against dust, insects, and animals is enhanced by drying in an enclosed structure.

Solar dryers are generally classified based on whether the product is directly exposed to insolation, the mode of air flow through the dryer, and the temperature of the air circulated to the drying chamber. In direct dryers, the crop is exposed to the sun but, in indirect dryers, the crop is placed in an enclosed drying chamber and thus shielded from insolation.

Airflow in the solar dryer may be natural or forced (by a fan or blower). Because of the higher airflow rates, solar collector efficiencies in forced-convection dryers are relatively higher than in natural-convection dryers.

Four types of dryers are commonly used in solar crop drying:

- Direct dryers with natural convection where the solar collector and drying chamber are combined;
- Direct dryers with natural convection where the solar collector and drying chamber are separate;
- Direct or indirect dryers with forced convection where the solar collector and drying chamber are separate; and
- Hybrid dryers that may be direct or indirect with forced convection where the solar collector and drying chamber are separate and with another form of heating the drying air, which may be electricity, gas, oil, or solid fuel.

Crop-Drying Requirements in Nigeria

Both rain-fed and irrigation agricultural production is practiced in Nigeria, and over 75% of the total crop produced is grown during the rainy season. Irrigated production is practiced mainly in northern Nigeria. Maize, millet, sorghum, cowpeas, soyabeans, groundnut (peanuts), and rice are the most common grains grown in Nigeria. The tubers include yam, cassava, and Irish and sweet potatoes, and the common vegetables are tomatoes, onions, and pepper. Because preservation facilities are inadequate or nonexistent, the prices of these commodities can fluctuate by over 500% during the year. Most of these crops may require drying after harvest for short- or long-term preservation.

The needs for grain-crop drying are more serious in the middle-belt and southern parts of Nigeria where the ambient relative humidity is relatively high during the harvest season. This makes it extremely difficult to dry crops naturally in the field. Maize is the major grain grown in these areas and is harvested between July and September, the wettest months. With the government ban on importation of maize, rice, and wheat for 1987, and attempts to substitute maize flour for wheat flour in bread production, efforts are being made to increase maize production, and thus a means of heating the relatively humid air to permit drying of the grains is needed. Unless this is done, grain losses will increase, and the expected positive net return from increased maize production will not be achieved.

In northern Nigeria, planting for rain-fed grain production normally starts in June. Over 95% of these grains dry down naturally in the field before final harvest, usually under favourable conditions (good sunshine and low relative humidity). However, supplemental heating for drying may be required for early harvested crops, in August and September, especially on the Jos Plateau, where the rain pattern and amounts are similar to those in the south, and in some good years when planting starts as early as April-May.

Tomato is the most widely used and important vegetable in Nigeria, and it is mainly produced in northern Nigeria through supplemental irrigation schemes. During both the dry- and wet-season harvests, tomatoes are abundant and cheap, but because preservation facilities are poor or nonexistent, the prices of this commodity can be five times higher at the end of harvest period. Tomatoes can be adequately preserved by cutting into slices and drying.

Groundnuts are mainly grown in northern Nigeria and the middle-belt and are harvested between August and September. The pods must be dried before shelling to avoid spoilage by microorganisms.

Other crops grown in both northern and southern Nigeria that may be preserved by drying include yam and cassava, in slices, and pepper. Rice is one of the most staple foods in Nigeria and, with the ban on its importation, more fields are being cultivated. At certain stages in the processing of rice, drying is required.

Solar drying can be applied to all these crop-drying needs.

Construction and Performance of Solar Crop Dryers

Two types of commercial-scale natural and forced convection solar-energy crop dryers have been designed, constructed, and tested at the Department of Agricultural Engineering, Institute for Agricultural Research of Ahmadu Bello University.

Description and Construction

One natural-convection solar crop dryer and one forced-convection solar crop dryer were built from readily available materials. Each of the dryers consists primarily of a flat-plate solar collector used to heat the drying air, drying bins or chambers where the crops are dried, and air circulation components such as fans, ducts, manifolds, and chimney.

The forced-convection solar crop dryer is 1.2 m wide and 15 m long. The framework for the solar collector was constructed from 12.5-mm plywood, which is usually available in 1.2 x 2.44 m sheets. The sheets were joined edge to edge with overlapping boards to obtain the 15-m length for the collector. The solar collector was covered with double-layered clear polyethylene sheets 4 μm thick. The collector back and edge insulation consisted of 25-mm fibreglass foam insulation and two sheets of 12.5-mm Celotex fibreboard. This combination gave an insulation thickness of 50 mm and a thermal resistance value of about 1.4 $m^2 \cdot {}^\circ C/W$. Sheets of 20-gauge galvanized steel welded together and painted with flat-black paint formed the absorber plate. The space between the absorber plate and top of the fibreboard was 25 mm and this formed the air passage or duct (Fig. 4a). Inlet and outlet air manifolds, constructed of plywood, were installed at the ends of the collector. The collector outlet air manifold was insulated with polystyrene board and connected to an insulated metal duct that was connected to the inlet of a cylindrical metal bin (Figs. 4b and 5).

The 1.5-m diameter, 1.8-m high cylindrical drying bin was constructed from 18-gauge galvanized steel. A ladder was provided for loading the bin from the top. The bottom of the bin was conical to aid in off-loading the crop through a gate closed by a sliding metal plate. An air-distribution system inside the drying bin provided uniform distribution of heated air. A centrifugal fan placed at the inlet end of the solar collector forced air through the solar collector and into the drying bin. To compare the effectiveness of forced circulation heated and unheated (natural) air drying, a second cylindrical drying bin similar to the first was constructed and connected through metal ducts to a similar centrifugal fan.

The natural-convection solar crop dryer consisted of a solar collector section for preheating the air and a drying chamber at the end of which was attached a chimney (Figs. 6 and 7). The framework for the solar collector and drying chamber was constructed with 19-mm plywood and both were insulated at the bottom and sides with fibreboard. The top of the solar collector and drying chamber was covered with transparent clear corrugated fibreglass sheets sloped slightly to allow rain water to drain. To minimize sagging effects, the fibreglass covers were supported at intervals by wood stringers nailed to the sides of the solar collector and drying chamber.

The collector-absorber plate was supported 0.08 m above the bottom of the collector. A divergent wooden manifold at the inlet of the collector helped to spread the air draft across the collector and drying chamber. The crop to be dried is kept on an extended-metal or perforated-metal screen supported also 0.08-m above the bottom of the drying chamber. Air chambers, therefore, existed below and above the absorber plate and drying chamber metal screen. The drying chamber consisted of four detachable units, each of which could hold 250 kg of crop in a layer of about 0.15-0.20 m. This is the maximum depth for effective drying because the airflow through the drying chamber, which is brought about by thermal forces, is limited to low levels. In the air circulation through the system, a chimney effect was obtained by mounting vertically at the end of the drying chamber a 3-m long, 0.3-m diameter cylindrical galvanized-metal chimney.

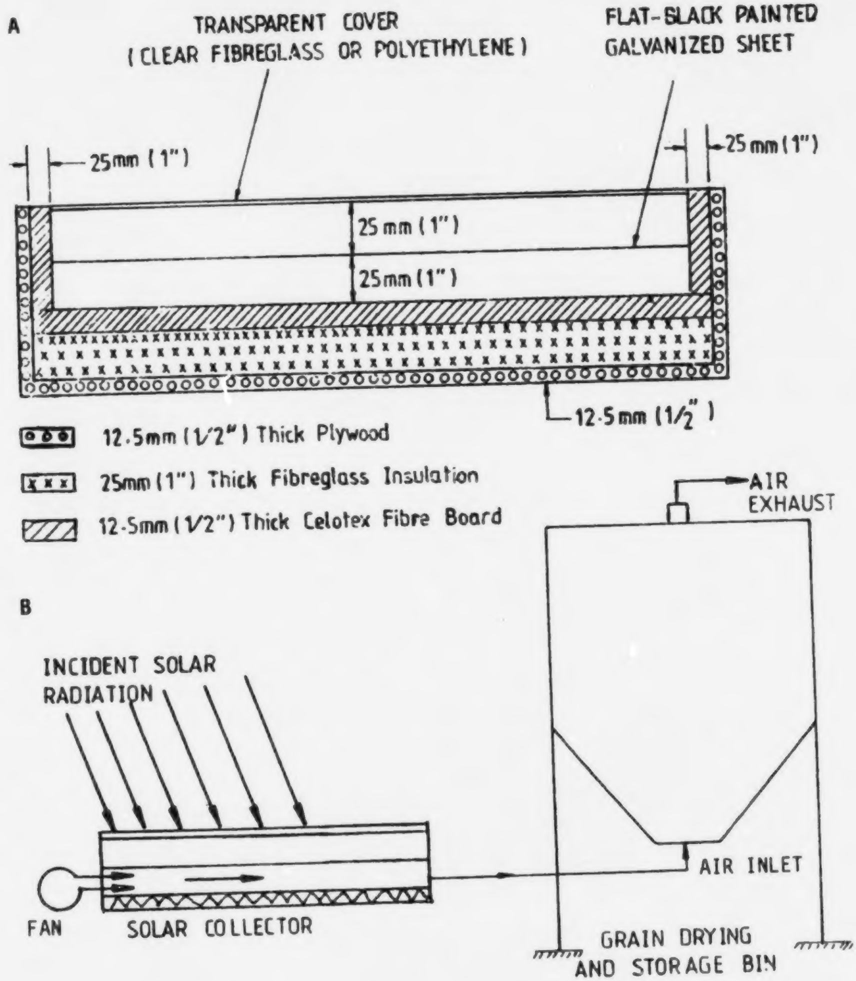

A
TRANSPARENT COVER
(CLEAR FIBREGLASS OR POLYETHYLENE)
FLAT-BLACK PAINTED
GALVANIZED SHEET
25mm (1")
25 mm (1")
25 mm (1")
25mm (1")
25mm (1")
12·5mm (1/2")
12.5mm (1/2") Thick Plywood
25mm (1") Thick Fibreglass Insulation
12·5mm (1/2") Thick Celotex Fibre Board
B
INCIDENT SOLAR
RADIATION
AIR
EXHAUST
AIR INLET
FAN
SOLAR COLLECTOR
GRAIN DRYING
AND STORAGE BIN

Fig. 4. Solar crop dryer: cross section of the standard-design flat-plate solar collector (a) and schematic for the solar collector and drying bin of the forced-convection dryer.

A hinged wooden window at both sides of each unit of the drying chamber was provided to aid in loading and unloading crops from the drying chamber. The windows had staple locks to seal the chamber tightly during drying.

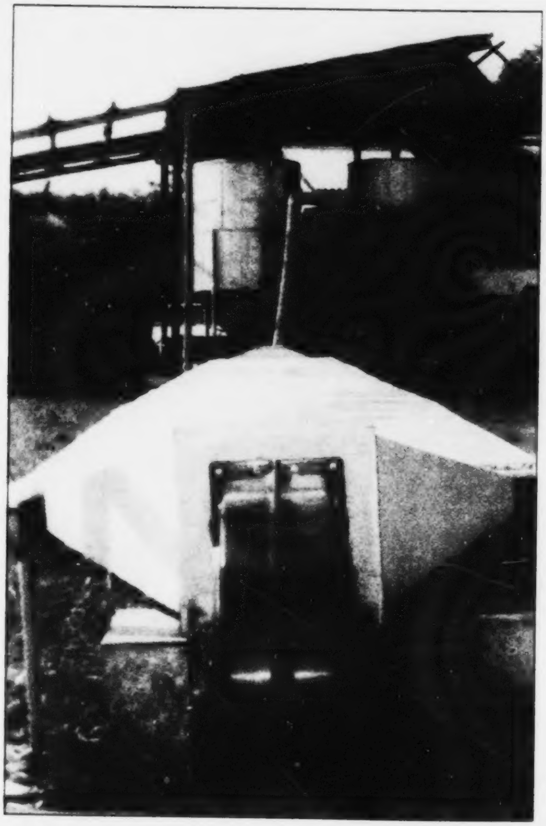


Fig. 5. Forced-convection solar crop dryer.

Theoretical Performance Analysis

As presented in detail in Arinze and Obi (1984a), and in Duffie and Beckman (1980), the collector useful energy gain is:

$$Q_u = M_a C_{pa}(T_o - T_i)$$
$$= A_c[\tau\alpha I_T - U_L(T_{pm} - T_i)]$$
$$= A_c \tau\alpha I_T - Q_L \qquad [1]$$

where

Q_u = collector useful energy gain (W)

M_a = mass flow rate of working fluid (kg/sec)

C_{pa} = specific heat of working fluid (J/kg per °C)

T_o = collector outlet fluid temperature (°C)

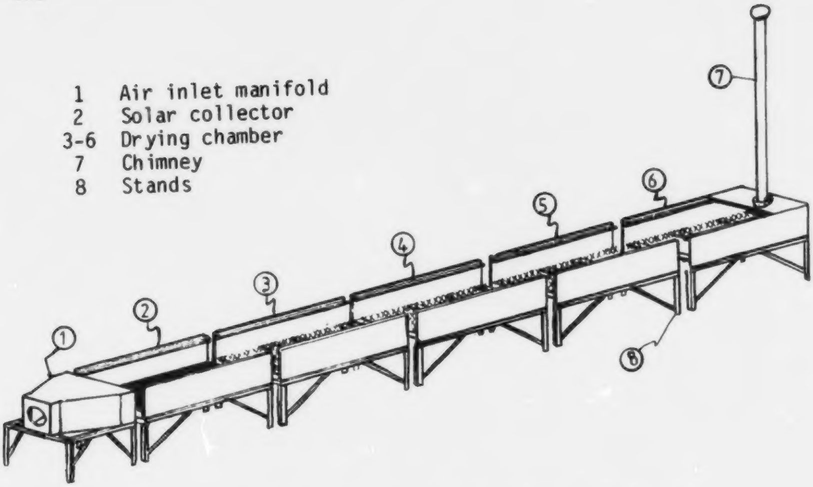


Fig. 6. Natural convection solar crop dryer.

T_i = collector inlet fluid temperature (°C)

A_c = collector area (m^2)

$\tau\alpha$ = effective transmittance-absorbance product for the collector cover and absorber plate

I_T = incident solar radiation on the collector cover (W/m^2)

U_L = overall collector heat loss coefficient (W/m^2 per °C)

T_{pm} = mean temperature of the collector absorber plate (°C)

= $T_i + (T_o - T_i)/2$, approximately

Q_L = rate of energy loss from the collector to the surroundings (W)

= $U_L A_c (T_{pm} - T_i)$.

For a given period, dt, the collector efficiency is (Duffie and Beckman 1980):

$$\eta = \int QUdt / \int A_c I_T dt \qquad [2]$$

Assuming that the exit air from the drying bin is at the ambient temperature, T_i, the overall energy balance of the system for the collector and dryer is:

$$\begin{aligned} Q_u &= A_c \ \tau\alpha I_T - Q_L \\ &= Q_D + Q_S \\ &= M_a \ C_{pa}(T_{Di} - T_i) + M_a C_{pa}(T_o - T_{Di}) \qquad [3] \end{aligned}$$

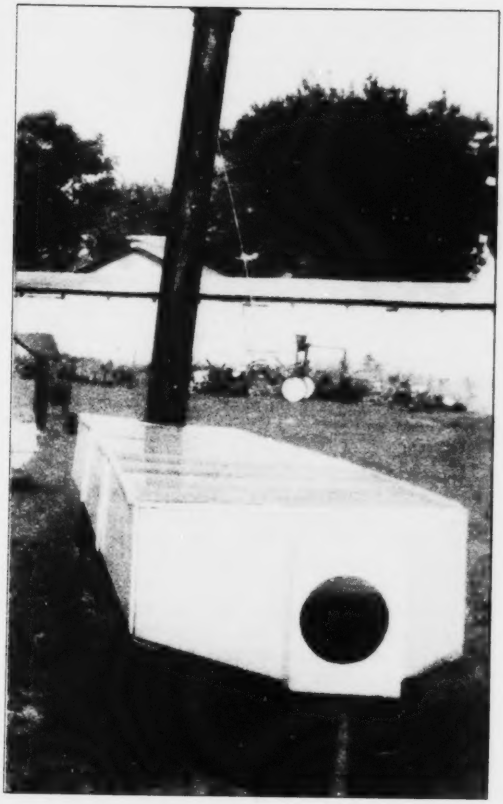


Fig. 7. Natural-convection solar crop dryer.

where

Q_D = rate of energy delivery to the dryer from the collector (W)

= $M_a C_{pa}(T_{Di} - T_i)$

Q_S = rate of energy loss in the ducts and manifolds from the collector to the dryer inlet (W)

= $M_a C_{pa}(T_o - T_{Di})$

T_{Di} = inlet air temperature to the dryer (°C)

T_o = outlet air temperature from the dryer or ambient temperature (°C).

The methods of evaluating all the terms in equations 1-3, including natural convection and forced convection mass flow of air through the collector-dryer system, are given in Arinze and Obi

(1984a), Arinze (1985), Duffie and Beckman (1980), and ASHRAE (1977). The equations were also used to predict the performance of the solar crop dryers and were programed in a digital computer.

Experimental Results and Discussion

The performances of the natural- and forced-convection solar crop dryers were investigated in several experiments. During the tests, various parameters, such as the total solar radiation incident on the collector cover, temperatures at different locations in the collector and drying chamber or bin, outdoor temperatures and relative humidity, and moisture content of the crop were measured. The total solar radiation was measured by an Eppley Black and White pyranometer and the output recorded by a chart recorder. Temperatures were measured at 1-hour intervals by copper-constantan thermocouples and the output recorded by a mini-thermocouple potentiometer. Mercury thermometers and bimetallic graduated thermometers were also used for temperature measurements. The moisture content of the crop placed in the dryer was determined by oven method by using an electrically heated laboratory oven set at 100°C. Static pressure drops at various locations along the flow channels were determined using a U-tube manometer or appropriate empirical equations from temperature measurements (ASHRAE 1977), and the measured or calculated pressures were used to determine various system airflows from fan-characteristic curves or appropriate empirical equations (Arinze 1985; ASHRAE 1977).

Continuous experimental tests for the forced-convection solar crop dryer were conducted from 7 to 12 September with air circulation through the solar collector and drying bin. The drying bin was filled with about 3.5 t of groundnut pods of about 39% initial moisture content (wet basis). Figures 8 and 9 show the measured and computer-predicted inlet and outlet air temperatures for the collector (Fig. 8) and useful heat gain, Q_U, for the collector (Fig. 9) for the forced-convection solar crop dryer for 1 day with average weather. The measured total horizontal solar radiation is also indicated in Fig. 8. The experimental collector efficiencies are shown in Fig. 10 for 7-12 September. (Each point in the figure represents the hourly collector efficiency plotted as a function of $(T_o - T_i)/I_T$ and the data for each day are represented by a distinct symbol.)

The drying bin for the unheated air dryer was also filled to the same depth with groundnut pods of the same initial moisture content. The moisture content of the groundnuts from the dryer with supplemental solar heat and without supplemental heat were determined by oven method at the end of each day of drying. The samples were taken from the bottom cone section (up to 0.6 m from the discharge gate), middle section (0.6-1.2 m), and top section (1.2-1.8 m). The moisture contents of the groundnuts in the bottom, middle, and top sections were 10.3, 18.4, and 30.6% (wet basis), respectively, at the end of the drying test for the forced-convection solar crop dryer. The bottom section, therefore, dried to safe moisture content within 5 days with solar supplemental heat. On the other hand, the moisture content of the crop in the bottom section of the forced-convection unheated air dryer was about 18% (wet basis), which was still unsafe for the crop after 5 days of drying, and mould formation was already noticed in the top section.

At the end of the 5th day, the contents of the two forced-

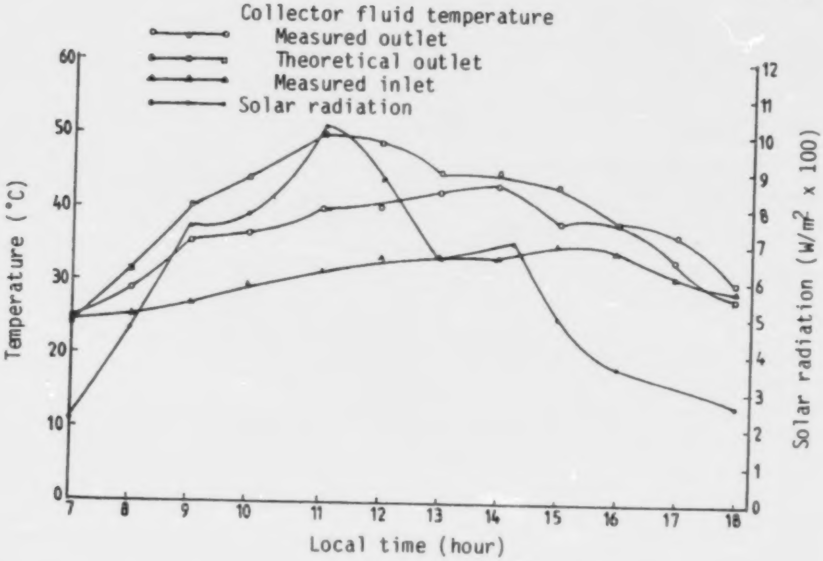


Fig. 8. Measured and theoretical collector fluid outlet and inlet temperatures, 10 September 1983.

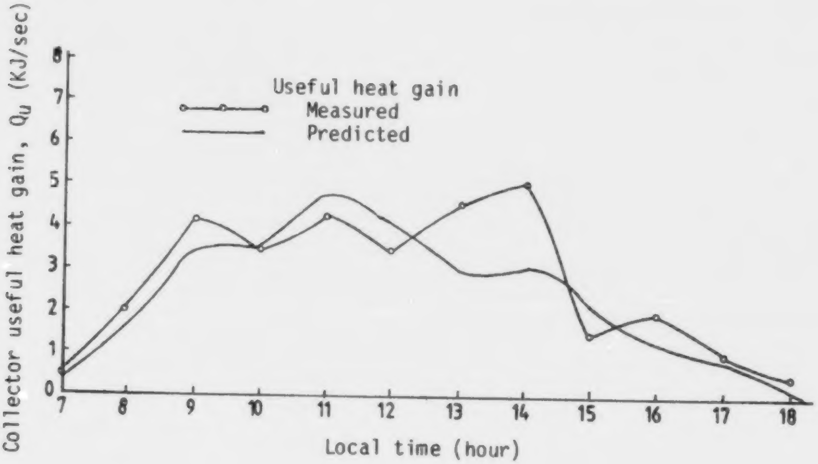


Fig. 9. Measured and theoretical useful heat gain by the collector, 10 September 1983.

convection dryers were partly emptied because the drying rate in the middle and top sections was not fast enough to prevent mould formation

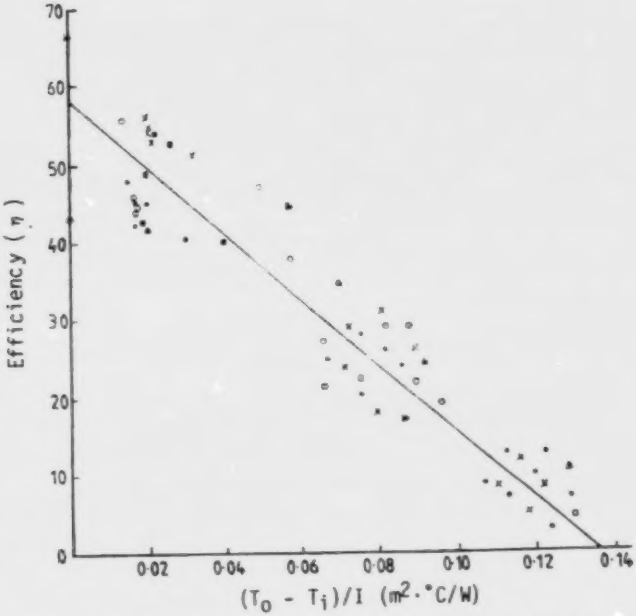


Fig. 10. Experimental thermal efficiency curves. Each symbol represents the data for a single day.

or self-heating. For this deep-bed dryer, a more effective and safer drying procedure would be step-wise filling for batch drying. This will obviously produce a better result and prevent crop spoilage.

One tonne of fresh maize cobs was dried with the natural convection solar crop dryer during harvest season for 5 consecutive days in September 1984. The maize cobs, with an initial kernel moisture content of 34.5% (wet basis), were spread to a depth of 0.15 m in the drying chamber. The kernel moisture contents in the inlet, middle, and outlet sections of the drying chamber were measured daily at 1900 hours.

Ambient, collector, and dryer air temperatures for the solar crop dryer during the test were generally highest between 1200 and 1400 hours (Fig. 11). At the end of the 5 consecutive days drying, the kernel moisture contents were 11.5, 13.3, and 14.5% (wet basis) for the inlet, middle, and outlet sections, respectively, giving a mean value of 13.1% for the entire dryer (Fig. 12): this mean moisture content is considered safe for storage. For the same initial kernel moisture content of 34.5%, it took 12 consecutive days for maize cobs spread outside to dry down to 15.5% kernel moisture content. This uncontrolled sun drying outside was interrupted several times by rain, which is usually very frequent in July, August, and September in Zaria.

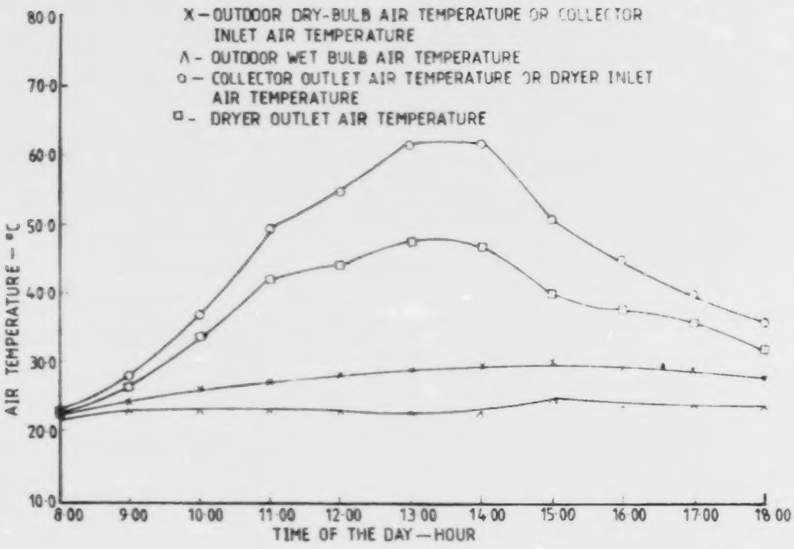


Fig. 11. Typical measured hourly outdoor (ambient), collector, and dryer air temperatures for the solar crop dryer during drying of maize cobs (22 September 1984).

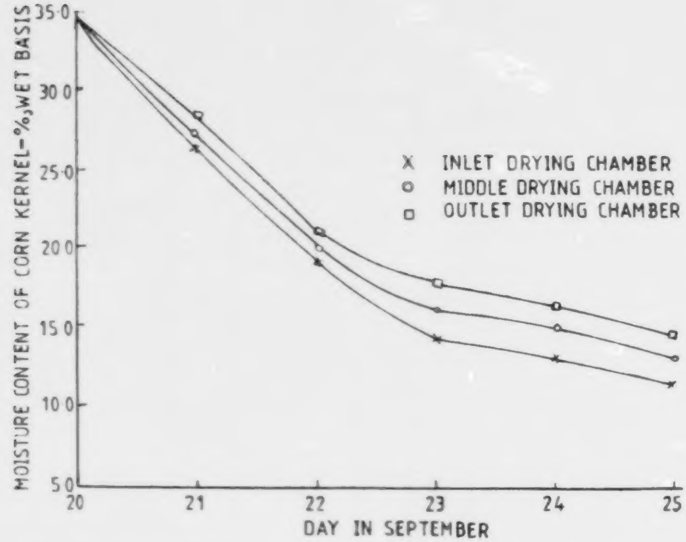


Fig. 12. Measured daily moisture content of maize kernels at three locations in the dryer during continuous drying of maize cobs with the solar crop dryer (20-25 September 1984).

In September 1984, about 50-mm thick layers of sliced yam and fresh tomatoes placed in the drying chamber of the natural-convection solar dryer dried to bone-dry condition in 1 and 2 days, respectively. About 50-mm thick layers of fresh pepper were also successfully dried to almost bone-dry condition in 2 days with the solar dryer. In addition, 520 kg of shelled groundnut (kernels) with initial moisture content of 9.8% (wet basis) and spread uniformly to a depth of 0.08 m in the 9.8-m drying chamber dried down to 6.3% moisture content in 12 hours on 1 May 1984. It took 2 days or 48 hours for about 50 kg of groundnut kernels of the same initial moisture content (9.8%) spread outside to the same depth on tarpaulin to dry naturally down to 6.5% moisture content under the sun. The relative advantage of the natural-convection solar crop dryer over the traditional sun drying is, therefore, evident from these tests.

The performance of direct natural-convection solar crop dryers as described here is influenced by the solar radiation absorption characteristics of the crop exposed to the sun. Earlier studies by Arinze (1978) and Arinze et al. (1979) indicated that the solar absorbances of most agricultural products, determined by calorimetric technique, are comparable to that of flat-black galvanized metal sheet (Fig. 13). By using the agricultural products as solar energy absorbers, as was done in the natural-convection solar crop dryer, the product's temperature would be higher than the drying air temperature. Under these conditions, the vapour pressure of water in the crop would be higher than that of water in the drying air. Thus, moisture will move out of the crop even though the relative humidity of the air is high. This is particularly advantageous in humid tropical areas or drying

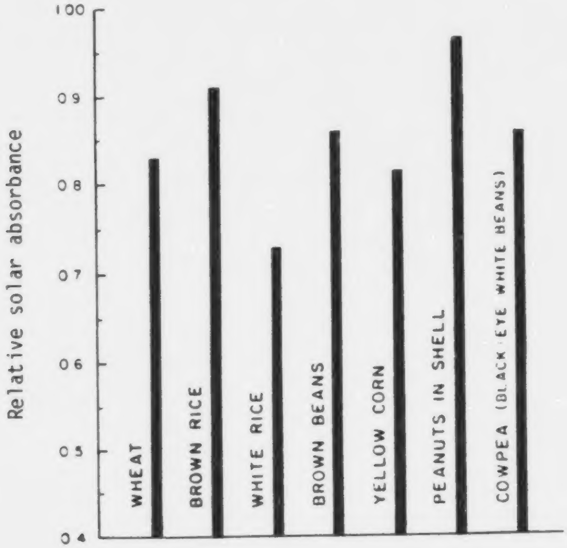


Fig. 13. Relative solar absorbance of various agricultural products compared to flat-black paint on galvanized metal (=1.00).

under cloudy conditions, especially in the southern and middle-belt parts of Nigeria.

Conclusion

Solar energy, which is sufficiently abundant in most developing countries and in Nigeria particularly, can be used to produce heat for various applications in homes, industry, and agriculture. Some low-temperature solar energy systems, such as are applied in crop drying and food processes, hot-water supply, and industrial process heat, are now cost effective and their widespread use in agricultural production and industry is highly recommended to conserve fossil fuels. Crop drying is necessary in Nigeria, and in most developing countries, for both long- and short-term crop preservation.

The results of the experimental tests on solar crop drying indicated that the forced-convection solar crop dryers performed satisfactorily in drying various agricultural products under varied weather conditions. The solar crop dryers have considerable advantages over the traditional uncontrolled sun-drying method in terms of much faster drying rate and handling convenience. Over 50% savings in time can be achieved by using the solar crop dryers as against the traditional sun drying. Further, by using the solar dryers, harvesting at higher moisture content is possible without fear of crop spoilage. The solar crop dryers can be made in various sizes, depending on the farmer's needs and capital availability. An intensive campaign is needed for adoption of solar crop-drying techniques for short- and long-term crop preservation in Nigeria and other tropical developing countries.

Acknowledgment -- The Department of Agricultural Engineering and the Institute for Agricultural Research, Ahmadu Bello University, Zaria, Nigeria, are acknowledged for providing funds and support for this research study.

References

Arinze, E.A. 1978. Solar energy absorption properties of some agricultural products. College of Engineering, University of Saskatchewan, Saskatoon, Canada. MSc thesis.

―――――― 1985. Design and performance evaluations of large-scale natural convection solar crop dryer. Paper presented at the National Solar Energy Conference of Solar Energy Society of Nigeria, Enugu, Nigeria.

Arinze, E.A., Obi, S.E. 1984a. Design and experimental evaluation of a solar energy crop drying system with heat storage. Nigerian Solar Energy Journal, 3, 54-70.

―――――― 1984b. Solar energy availability and prediction in northern Nigeria. Nigerian Solar Energy Journal, 3, 3-10.

Arinze, E.A., Scheonau, G.J., Bigsby, F.W. 1979. Solar energy absorption properties of some agricultural products. American Society of Agricultural Engineers, St Joseph, MI, USA. Paper 79-3071.

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). 1977. ASHRAE handbook of fundamentals. ASHRAE, New York, NY, USA.

Duffie, J.A., Beckman, W.A. 1980. Solar engineering of thermal processes. John Wiley, New York, NY, USA.

DESIGN, INSTALLATION, AND PRELIMINARY TESTING OF A NATURAL-CIRCULATION SOLAR-ENERGY TROPICAL-CROP DRYER

P.D. Fleming,[1] O.V. Ekechukwu,[2] B. Norton,[1] and S.D. Probert[1]

Abstract — *An internationally unique, large-scale, experimental facility for evaluating the performance of solar-energy crop dryers was installed and commissioned at the Nigerian National Centre for Energy Research and Development. This facility enables the testing and performance evaluation of various configurations of integral-type natural-circulation solar-energy tropical-crop dryers to be undertaken. A rigorous computer-based simulation model of the behaviour of the dryers was developed concurrently. The empirical data were used to assess the veracity of the predictions from the theoretical simulation model. Thus, shortcomings within the simulation were identified and appropriate modifications made to the model. The fully validated model will be used to determine the optimal system configurations for several tropical crops. An important feature of this experimental facility is its comprehensive data-acquisition capabilities. The computer-based system takes signals from over 100 sensors. These include measurements within the dryer of the moisture loss from the crop; the air temperatures, humidities, and velocities; and the crop temperatures. In addition, a weather station monitors the ambient air temperature and humidity, speed and direction of the wind, the diffuse and direct components of solar radiation, and the daily rainfall. This massive amount of data is stored on magnetic discs and researchers at Nsukka and at Cranfield are currently analyzing it. From the analyses of these data, the behaviour of solar crop dryers will be understood better and improvements to dryer design will be proposed. This is the first time that such a large-scale solar dryer has been so comprehensively monitored in a tropical environment. This paper reports the design and installation of the full-scale experimental facility. The dryer-monitoring philosophy is also outlined and preliminary data are presented that describe the behaviour and performance of one dryer design.*

---

[1] Solar Energy Technology Centre, School of Mechanical Engineering, Cranfield Institute of Technology, Bedford, U.K.

[2] National Centre for Energy Research and Development, University of Nigeria, Nsukka, Anambra State, Nigeria.

Introduction

In many rural locations in Nigeria, grid-connected electricity is either unavailable, unreliable, or expensive. Thus, in such areas, crop-drying systems that employ motor-driven fans or electrical heating are inappropriate. The large initial and running costs of dryers powered by fossil fuel present such financial barriers that they are rarely adopted by small-scale farmers. In such conditions, natural-circulation solar-energy crop dryers appear to be increasingly attractive as commercial propositions. The advantage of such a dryer is that it requires a smaller area of land than would be needed to dry similar amounts of crop in the open under traditional systems. Another advantage is that it will yield a relatively high quality dry crop, because insects and rodents are unlikely to infest the crop during drying. The drying period is shortened compared with open-air drying and the crop is protected from sudden rainfall. Thus, the relatively low capital and running costs of these crop dryers and the improved crop quality achieved after drying enable these systems to compete economically with traditional open-sun drying.

Solar Drying

Open-to-sun Drying

Two traditional approaches are used in passive solar crop drying in tropical countries.

- The plant bearing the crop dies, either in contact with the soil or is cut down but not removed, i.e., drying takes place in situ.
- The crop is placed on floors or trays exposed to solar radiation and to natural air currents. The crop should be stirred occasionally to expose different parts of it to the sun and thus speed the removal of the saturated air.

Despite the rudimentary nature of the processes involved, such techniques still remain in common use because the power requirements (i.e., from the solar radiation and the air's enthalpy) are readily available in the ambient environment. Because little or no capital investment is required, these are frequently the only commercially viable methods by which to dry agricultural produce in developing countries. Thus, at present, a large proportion of the world's supply of dried fruits and vegetables continues to be sun-dried in the open. Because the crop is exposed to unexpected rains, winds, infestation by insects, and contamination by rodents and other animals, the quality of the dried product is often degraded seriously, sometimes becoming inedible. Although more efficient solar-drying methods are being developed, the traditional drying methods do have three important positive attributes: low capital and running costs and independence from fuel supplies.

Natural-circulation Solar-energy Crop Dryers

In natural-circulation systems, solar-heated air is circulated through the crop by buoyancy forces or as a result of wind pressure, either alone or in combination. These dryers are often referred to as passive systems to distinguish them from those in which a fan forces the air through the crop. The latter can be termed active solar dryers.

Two generic types of natural-circulation solar-energy dryers have evolved, both of which retain many of the advantages of traditional open-to-sun drying: distributed and integral systems.

Distributed System

The crop is spread on shelves in a "hot" box (Fig. 1) and heated by circulating air that is warmed during its flow through a low pressure-drop thermosyphonic solar collector (Norton and Probert 1984). Because the material to be dried is not subjected to direct sunshine, caramelization and heat damage do not occur.

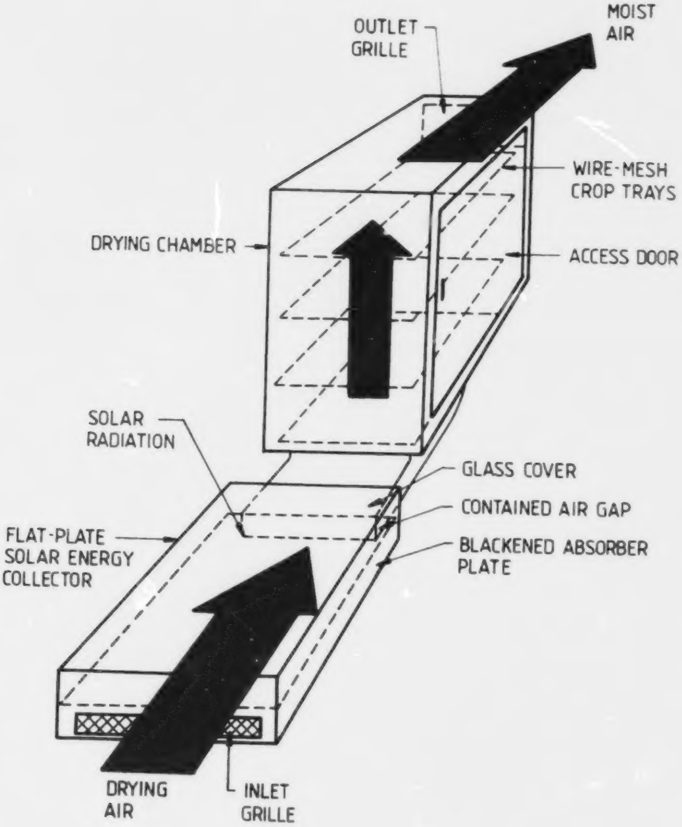

OUTLET GRILLE
MOIST AIR
WIRE-MESH CROP TRAYS
DRYING CHAMBER
ACCESS DOOR
SOLAR RADIATION
GLASS COVER
CONTAINED AIR GAP
FLAT-PLATE SOLAR ENERGY COLLECTOR
BLACKENED ABSORBER PLATE
DRYING AIR
INLET GRILLE

Fig. 1. Distributed natural-circulation solar-energy crop dryer. (Heavy arrows show direction of airflow.)

Integral System

The crop is placed in a drying chamber (Fig. 2) with transparent walls that allow the insolation necessary for the drying process to be transmitted. This process enhances the proper colour "ripening" of greenish fruits by allowing, during dehydration, residual chlorophyll in the tissue to decompose under direct solar radiation. The major

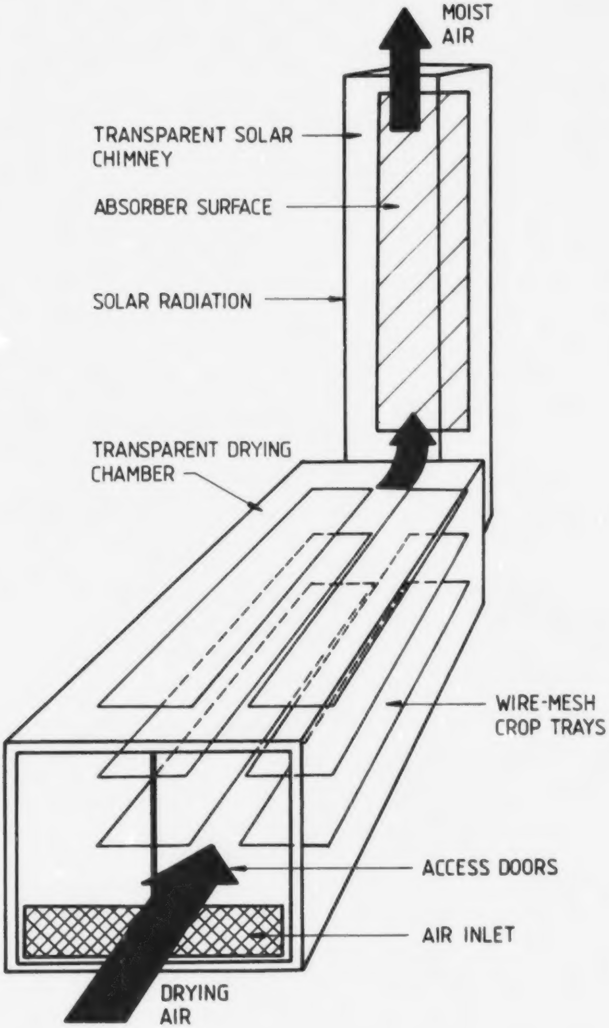

MOIST AIR
TRANSPARENT SOLAR CHIMNEY
ABSORBER SURFACE
SOLAR RADIATION
TRANSPARENT DRYING CHAMBER
WIRE-MESH CROP TRAYS
ACCESS DOORS
AIR INLET
DRYING AIR

Fig. 2. Integral natural-circulation solar-energy crop dryer. (Heavy arrows show direction of airflow.)

drawbacks are the risk of local overheating, causing crop damage, and the relatively slow overall drying rates achieved due to poor vapour removal. To overcome these limitations, a "solar chimney" can be used to increase the buoyancy force imposed on the air stream. This increases airflow velocity and, thus, speeds moisture removal.

Experimental Facility

The dryer tested in this study is of the integral type (Fig. 2). In actual use, such dryers have often failed to achieve the expected performance or popularity. This has been due to bad design, relatively high initial capital cost, and low drying capacities and the fact that high product quality has not been seriously considered. Accordingly, the performance of the experimental dryer is being optimized with respect to five factors:

- Use of readily available indigenous labour and materials for construction;
- Commercial viability, i.e., low capital and running costs;
- Short drying periods to attain high rates of product throughput;
- Large drying capacity; and
- Good final product quality.

Crop Dryer Design

The solar-energy tropical-crop dryer consists of a transparent semicylindrical tunnel with a cylindrical "chimney" rising vertically out of one end (Fig. 3). This relatively simple design is constructed from a galvanized steel framework clad with polyethylene sheet. The crop and a vertical black absorber curtain within the chimney absorb the solar energy and, thus, are warmed. They, in turn, heat the surrounding air. As this hot air rises and flows up the chimney, fresh air is drawn in at the other end of the dryer. This simple operation involves no additional power and provides a flow of air through the dryer.

The main parameters that influence the temperatures and airflow inside the dryer are the height of the solar chimney, the area and position of the absorbing curtain within the chimney, the length of the dryer, the area of the air intake into the dryer, the packing density of the crop within the dryer, and the drying characteristics of the crop being dried.

The drying chamber was a commercially available semicylindrical plastic-clad greenhouse that had been modified and augmented for research purposes. Because the trays that held the crops to be dried were suspended from load cells to measure the weight of the crop, the supporting framework was over-engineered structurally (Fig. 4). Subsequent commercial designs would not need this additional support because the crop would be placed on shelves or pallets. Thus, commercial dryers should be easier and cheaper to construct. In addition to the modifications of the framework, three other changes were made to the original "greenhouse" configuration:

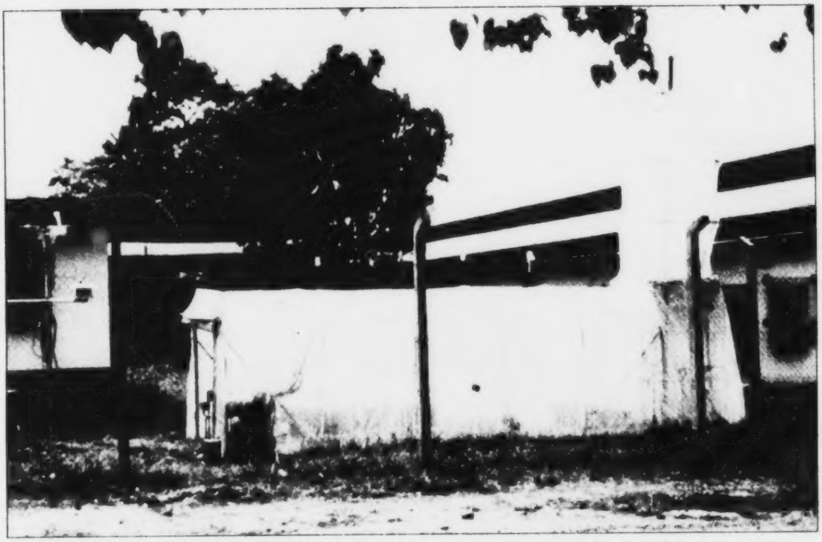


Fig. 3. Experimental natural-circulation solar-energy tropical-crop dryer at Nsukka, Nigeria.

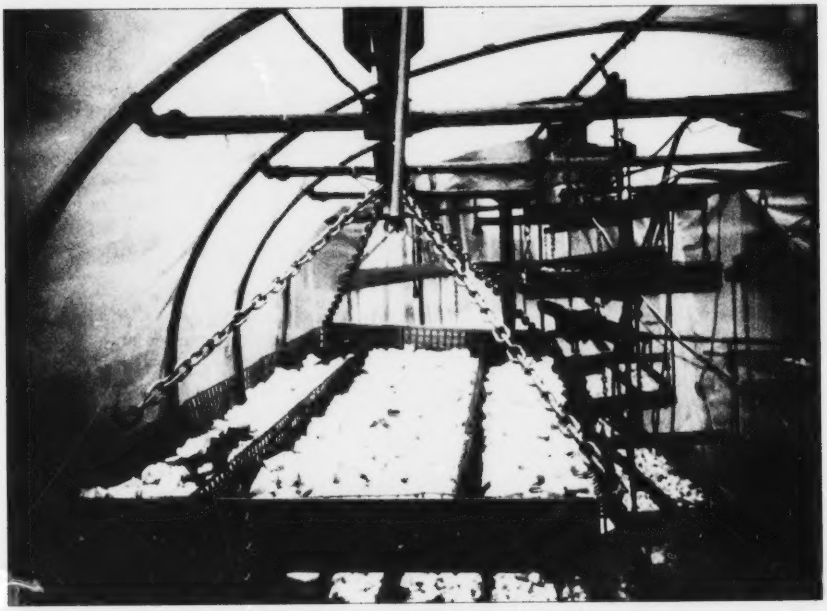


Fig. 4. Heavy internal framework of experimental crop dryer -- tray loaded with cassava.

- An additional framework was constructed at one end of the dryer to support the large solar chimney structure;
- The polyethylene cladding for both the drying chamber and the solar chimney was treated so as to be suitable for operation in tropical climates; and
- The translucent solar chimney was draped internally with a selective surface to absorb the solar radiation.

Crop Dryer Installation

The dryer and its extensive monitoring equipment were assembled outdoors, initially at the laboratory of the Solar Energy Technology Centre at Cranfield, U.K., in July 1985. The dryer's constructional details were appraised and modified where required. This also allowed time for the sensors and the computer software to be rigorously tested. The final site for the dryer was at the National Centre for Energy Research and Development at the University of Nigeria, Nsukka (6.8° N). The site was selected because at no time would the dryer be in shadow and it was relatively close (less than 20 m) from the adjacent building that housed the monitoring equipment.

"Anti-hot-spot" tape applied to the outer surfaces of the galvanized steel framework thermally insulated it from the polyethylene cladding. This prevented undesirable localized heating of the cladding that would severely shorten its useful life. The polyethylene cladding totally enclosed the drying chamber.

The height of the solar chimney could be adjusted by one person using a rope that passed over a pulley at the top of the 6.7-m galvanized steel pole and was connected to the top-most hoop of the chimney-support structure.

Data Acquisition System

The data-acquisition equipment was housed in a building adjacent to the crop dryer and was connected to sensors in the dryer by 14 lengths of 12-way cable. The microcomputer converted the sensor signals to appropriate parametric values that were displayed graphically or tabulated on the monitor and stored electronically by the computer.

Data logging was accomplished by a modular system in which a microcomputer was used in conjunction with a specialist instrumentation peripheral. Both the computer and the peripheral were equipped with the IEEE-488 instrument interface: the established means for configuring laboratory-scale data-collection systems. Almost unlimited expansion of the present system is possible by simply adding further IEEE-488-compatible devices to the same interface.

The system consisted of the microcomputer, monitor, printer, disc drive, IEEE-488 interface, two multiapplication peripheral systems (MAPS), a digital voltmeter, and specialized signal conditioners for the air velocity meters (Fig. 5). The MAPS scanned the sensor channels and the digital voltmeter then measured the resulting voltage received from each of the 105 channels. The gathered data were then

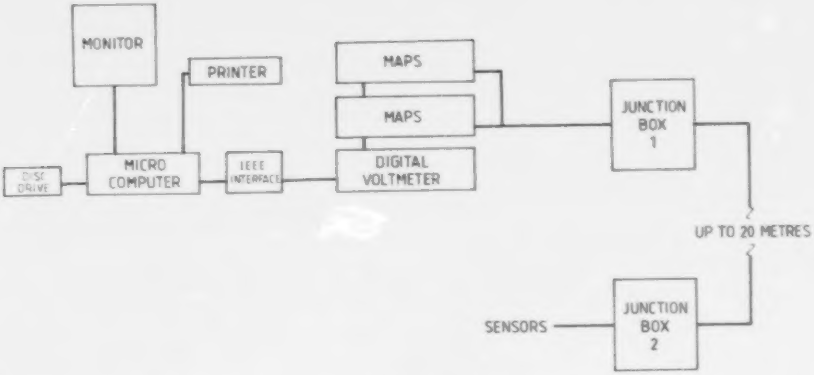


Fig. 5. Schematic of the data acquisition system.

recorded onto a floppy disc. Both present and previously acquired data could be displayed graphically or tabulated on the monitor. In addition, printed copies were provided by a dot-matrix printer.

Junction boxes containing the cables and their terminal blocks were used to convey the sensor signals to the MAPS. Thus, each of the sensors could be disconnected easily at the dryer (i.e., at the second junction box). The junction boxes could be up to 20 m apart.

To ensure that the power supply gave both a constant voltage and frequency that would not damage any components of the electronic equipment, a static uninterruptible power supply, with a 30-min battery back-up was used. This totally isolated the data-logging power supply from the mains supply and provided an effective solution to the problems of blackouts, microbreaks, electrical noise, voltage dips, and frequency fluctuations.

The pair of microcomputers were Acorn BBC (model B) that had two main functions: one was used to control the data acquisition system, and the other to analyze the resulting data. Recorded data were stored on 80-track double-sided discs, each capable of storing up to 203,000 bytes of data on each side. As each individual recording took up 360 bytes of disc space, 563 recordings could be stored on each disc side. Because the data were acquired at a rate of 48 recordings per day, i.e., one every 30 min, data for 22 days could be stored on each disc.

Details of the sensors used in the data acquisition system are shown in Table 1. All the sensors gave voltage outputs (mV) except the rain gauge and the temperature/humidity sensors. The latter sensors had current outputs (mA) that were directly proportional to temperature or humidity respectively. Accordingly, current-to-voltage terminator cards were used to enable the digital voltmeter to read their output signals as voltages for computer manipulation. For the rain gauge, each tip of the tipping-bucket closed the contacts of an event counter. As the event-counter module can accept five inputs, there is a spare capacity of four.

Table. 1. Sensors used to monitor the dryer's performance.

Sensor type	Parameter measured	Number of sensors		Units of data output
		Installed	Potential	
Load cell	Weight loss	15	30	kg
Thermocouple	Various temperatures	20	20	°C
Temperature/humidity	Air temperature Air humidity	15 15	15 15	°C %
Air velocity	Air velocity	12	14	m/sec
Solarimeter and shadow band	Diffuse solar radiation	1	1	W/m^2
Solarimeter	Total solar radiation	1	1	W/m^2
Anemometer	Wind speed	1	1	m/sec
Wind vane	Wind direction	1	1	degrees
Platinum resistance thermometer	Wet- and dry-bulb temperatures	1 1	1 1	°C °C
Rain gauge	Daily rainfall	1	5	mm/day

Computer Software

The data acquisition and manipulation software developed specifically for this project has two major parts: the main data-acquisition program and the data reduction, analysis, and presentation programs.

The main program, which runs on one microcomputer, controls the operation of the data-logging equipment, displays the recorded time, and stores the data on floppy discs. Thus, it was capable of:

- Calculating the real time continually;
- Reading all the sensors when required and taking readings of particular sensors under no-load conditions;
- Applying conversion factors (and zero-offsets where necessary) to all these sensor readings to give the appropriate engineering values;
- Storing these basic engineering values on floppy discs;
- Displaying all the recorded data for a particular time on the monitor screen in tabular form;
- Displaying all the data of any specified type of sensor for a 2.5-hour period on the monitor screen in tabular form;
- Displaying the previous readings of any specified sensor in tabular form;
- Displaying the readings of the load cells under no-load condition (i.e., the zero-offset values); and
- Plotting previous values of a specified sensor on the monitor screen.

Because the system included unoccupied channels, it was readily expandable to include and handle data from extra sensors and this was specifically catered for in the software. All the channels read by the digital voltmeter were stored on the disc irrespective of whether there was a sensor connected to that channel; however, the monitor only displayed the actual sensor values.

The data-analysis computer was completely independent of the monitoring computer, thus allowing continuous monitoring of the experimental facility. In reality, however, only the climatological data were continuously recorded (the averaged values being stored every 30 min) and the dryer was monitored only when a test was being undertaken. A dual disc-drive system was used to enable one drive to record just the climatological data and the other to record data from both the dryer and the weather station.

Experimental Data

Experimental data have been obtained from the dryer operating under a variety of climatological conditions. Figures 6-11 illustrate the diurnal variation of system parameters and applied conditions for

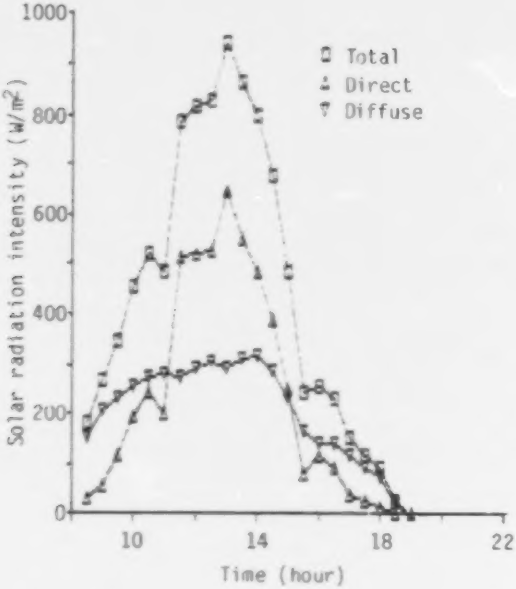


Fig. 6. Diurnal variation of solar radiation intensity.

one particular test carried out on 7 May 1986. The crop being dried was cassava chopped into rough cubes (about 0.02 x 0.02 x 0.02 m).

The diurnal variation of the direct, diffuse, and total solar radiation intensities during the test period (Fig. 6) shows a relatively high direct component of solar radiation. The effect of the sudden reduction in insolation around 1400 hours is clearly identifiable in Figs. 7-11. In Fig. 7, ambient relative humidity rises after 1400 hours whereas dryer air temperature falls (Fig. 8), air relative humidities rise (Fig. 9), and ground temperatures fall (Fig. 10) during this period. However, the reduction in solar radiation intensity has a lesser effect upon the ground temperature than the air temperature within the drying chamber (Fig. 8 vs Fig. 9).

Although ground temperature increases along the length of the dryer (Fig. 8), the crop dries faster nearer the entrance of the dryer for the particular air velocity (0.5 m/sec) encountered (Fig. 11). This occurs because the air is both warmer (Fig. 9) and drier (Fig. 10) toward the dryer entrance than in the middle section or at the drying chamber exit because it has absorbed evaporated moisture from the crop as it progresses down the length of the dryer.

The air temperature within the drying chamber was significantly higher than the ambient temperature (up to 15°C) and the relative humidity of the drying air fell dramatically to around 25%, compared with an ambient of about 60%. Thus, the air within the drying chamber is more capable of drying crops than the ambient air. The results

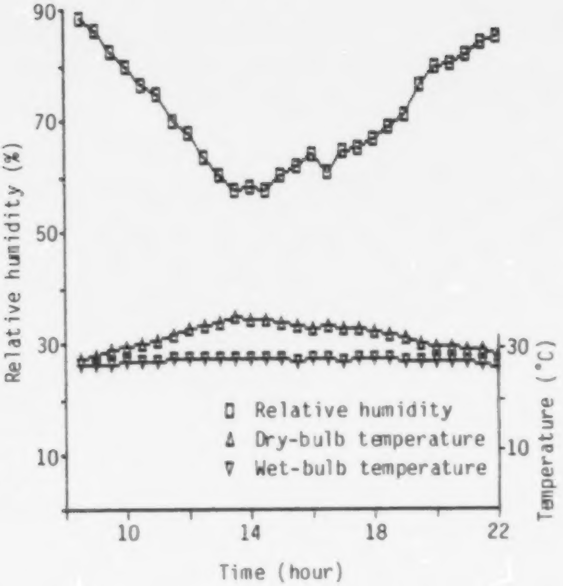


Fig. 7. Diurnal variation in relative humidity and dry- and wet-bulb temperatures.

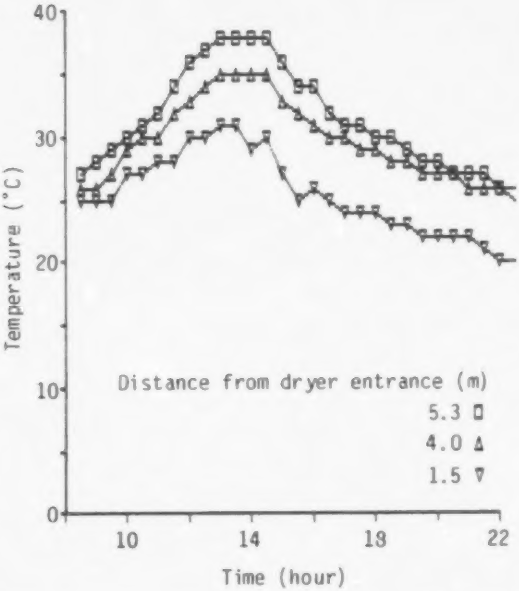


Fig. 8. Diurnal variation in ground temperature at three locations within the drying chamber.

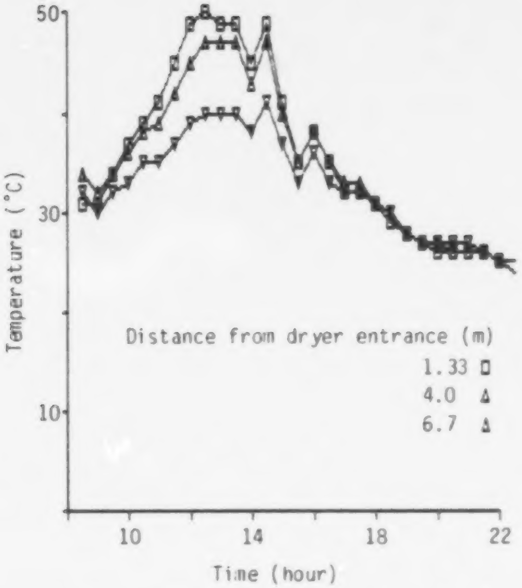


Fig. 9. Diurnal variation in air temperature (1.8 m above ground) at three locations within the drying chamber.

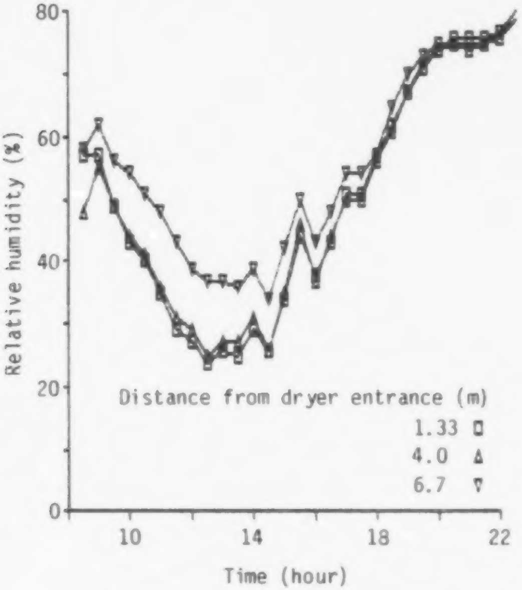


Fig. 10. Diurnal variation in air relative humidity (1.8 m above ground) at three locations within the drying chamber.

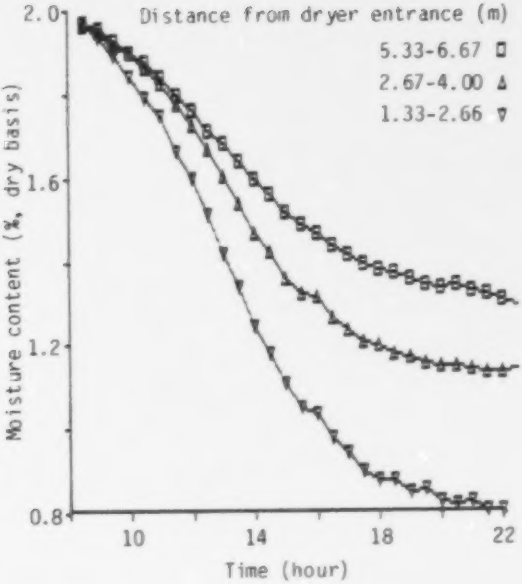


Fig. 11. Drying profiles over time of cassava cubes at three locations within the drying chamber.

from the test with cassava (Fig. 11) compare favourably with other solar drying tests using cassava (Roa 1974).

Future Research

The experimental research will continue at Nsukka for the forseeable future to gain as much knowledge of the dryer's performance under a variety of climatic conditions and with many different crops. Although this experimental dryer was manufactured in the U.K., we are currently preparing designs and assessing the feasibility of manufacturing it in Nigeria for the second stage of the research and development work. These second generation dryers will be designed and built in Nigeria using locally available materials, labour, and equipment. Field testing of these locally manufactured commercial dryers should start in 1987.

Three complementary principal research topics are envisaged for future research projects.

Development of Solar Dryer Design Charts

Dryer design charts do not currently exist. However, the computer-based simulation models that are now being investigated to describe the dryer's behaviour and predict its performance will form the basis from which to develop them. When they are available, they will enable farmers and agricultural extension workers to decide readily whether a natural-circulation solar dryer is suitable for a particular geographic location or type of crop and they will indicate clearly the most appropriate design of solar crop dryer.

Determination of the Drying Characteristics of Tropical Crops

During the present study, we found that, for many tropical crops and particularly root crops, the drying characteristics are not fully understood. Such fundamental information is vital to the effective design of any tropical-crop dryer. Future research work should include a program to determine accurately this empirically derived information.

Assessment of Local Manufacture and Effectiveness

The next stage of the project should also include the local manufacture of crop dryers for particular types of crop in specific locations. These dryers would be subject to normal operating constraints and their performance would be monitored at a limited level. Several dryers would be located at Nsukka so that they could be comprehensively monitored and compared with those operating in the "real world" and with existing drying methods.

Conclusion

The results from the large-scale experimental facility in Nigeria have demonstrated the superior drying characteristics of integral-type thermosyphon solar dryers over traditional open-sun drying. In particular, the air temperatures and humidities achieved within the drying chamber are suitable for the drying of cassava.

A comprehensive computer-based simulation model is currently being developed to describe the dryer's behaviour and to predict its drying performance for a wide range of crops. From these preliminary simulations, the models will then be modified to include many types of natural-circulation solar-energy crop dryers. Such models will form the basis with which to develop a series of design charts. Such solar dryer design charts would enable farmers to decide readily whether a solar dryer is suitable for their particular location and type of crop. If a dryer is appropriate, then the charts will indicate clearly the most appropriate design.

Acknowledgment -- The financial support of the Commission of the European Communities, Brussels, Belgium, and of the British Council, London, U.K., is gratefully acknowledged.

References

Norton, B., Probert, S.D. 1984. Solar energy stimulated, open-looped thermosyphonic air-heaters. Applied Energy, 17, 217-234.

Roa, G. 1974. Natural drying of cassava. Department of Agricultural Engineering, Michigan State University, East Lansing, MI, USA. PhD thesis.

EVALUATION OF THREE TYPES OF SOLAR DRYERS FOR NIGERIAN CROPS

J.C. Igbeka[1]

Abstract -- *Three types of solar dryers were compared -- a solar concentrator with a drying chamber, a flat-plate collector with an in-bin storage/dryer, and a flat-plate collector-cum-dryer. In the last two, the crops themselves absorb solar heat. Although the concentrator produced the greatest temperature difference, its drying efficiency was the lowest. The third type of dryer was found to give the best drying result; but the modified version of the second design was recommended for adoption for the rural farmers. Recommendations that can help designers of solar dryers are given. Factors that affect the drying efficiency of solar dryers in the humid tropics were also investigated. The performance of solar dryers during the dry hot season was found to be better than during the wet humid season. The seasons also affected the moisture content of the crops at harvest. The sociocultural standard of the farmers was found not to inhibit the adoption of solar dryers. The need for the use of locally available materials for the construction of solar dryers is emphasized.*

Introduction

Nigeria's oil reserves have been estimated to last for another 20 years, thus, advantage must be taken of the sunshine that is available all year round as a result of the country's location in the tropics. The humid southern part of the country, represented by the city of Ibadan, records its lowest mean monthly sunshine (88 hours) in August (wet cloudy season) but can receive as much as 235 hours/month between November and January (dry hot season) (Igbeka 1980). The equivalent values are higher in the northern, savannah, part of the country.

Solar energy is fast becoming an alternative source of energy because of the high rate of depletion of the conventional energy sources. It is preferred to other alternative sources of energy, such as wind and shale, because it is abundant, inexhaustible, and non-polluting. Equally, it can be tapped at a relatively low cost and has no associated dangers of fire or other hazards. Therefore, the use and application of solar energy for rural development cannot be overemphasized.

---

[1] Department of Agricultural Engineering, University of Ibadan, Ibadan, Nigeria.

One of the applications of solar energy is in the drying of agricultural and food materials. However, many different types of crops are available in Nigeria, depending on the ecological location, and the successful application of solar energy in drying these crops or foods will depend on several factors: average temperature, relative humidity, and insolation or sunshine of the location; initial moisture content of the crop; and socioeconomic status of the people. The basic problem of using solar dryers in Nigeria are high air relative humidity, especially in the southern part of the country; high initial moisture content of crops during harvest; and, sometimes, low insolation during harvest period.

The objectives of this paper are fourfold: first, to review the work done in applying solar energy, especially in drying food, in Nigeria; second, to analyze and compare three types of solar dryers; third, to identify the socioeconomic factors that influence the implementation of solar energy application (drying) in rural areas; and, fourth, to recommend areas for future research and development work. It must be noted that only passive solar systems, as the systems most adaptable to rural areas, are considered.

Review of Past Work in Nigeria

Most of the research on solar-energy application in Nigeria has been done in the departments of physics, mechanical engineering, and agricultural engineering of Nigerian universities and in some research institutions. Unfortunately, most of this research has not been published but only documented as project or research reports in the various institutions. Thus, it has been very difficult to review all the efforts made in solar-energy application. The only forum where the work on this topic can be coordinated and discussed is the annual conference of the Solar Energy Society of Nigeria. Most of the papers presented at this conference are published in The Nigerian Journal of Solar Energy.

One element of solar energy research is the determination of the input parameters, particularly the solar radiation available for collection either directly (Ezeilo 1979; Bamiro and Ideriah 1982; Doyle 1982; Ideriah and Bamiro 1982) or through mathematical models (Ezekwe and Ezeilo 1981; Ideriah 1981; Arinze 1982; Bamiro 1983). These researchers, because of their backgrounds, were much more interested in the collector performance than in the application of the collected energy.

Some of the work done in applying solar energy was in water heating and photovoltaic storage for water pumping and refrigeration. Tani (1979), working in the International Institute of Tropical Agriculture (IITA) at Ibadan, collected and stored solar energy in photovoltaic cells and later used it for lighting, pumping water, and operating a refrigerator for rural conditions. At the same time, a great deal of meteorological data were collected from this station: they included sunshine hours, insolation, relative humidity, and average daily temperature (Fig. 1).

A third element of solar energy research is the design of appliances. Chendo and Schmitter (1982) investigated the performance of a Perspex-covered solar still. They found that, for rural areas,

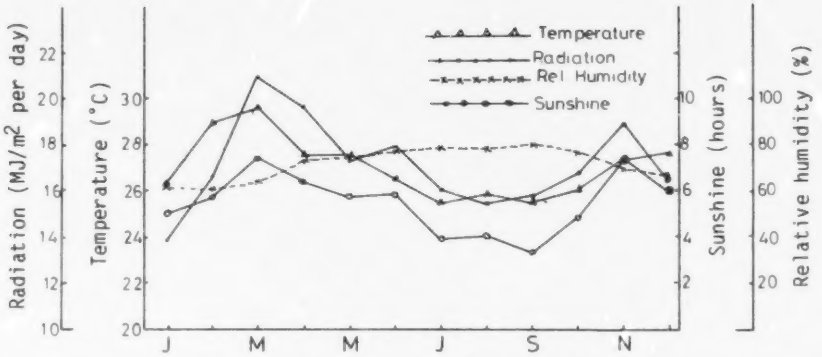


Fig. 1. Monthly average of daily total radiation, temperature, relative humidity, and sunshine duration in Ibadan, Nigeria.

Perspex was preferable to glass because it was less likely than glass to be broken by stray stones and animals. This view was confirmed by Araoye (1984) when he evaluated the performance of a solar dryer/storage system.

Adebiyi (1982) designed, constructed, and evaluated a solar steam unit made from locally available materials. He found the overall efficiency of the solar heater to be 69%, which is quite high. His design has been quite widely applied in the rural areas of the northern part of Nigeria.

Solar Dryers

Solar drying research has been going on in Nigeria for 10 years mostly in universities and polytechnic colleges in the departments of agricultural and mechanical engineering. Some of the work has been published in journals or conference proceedings but other work remains unpublished although it has been documented as project reports.

Ofi (1982) constructed and evaluated a solar dryer using a flat-plate collector. Although he did not dry any crops with it, he obtained a plenum chamber temperature that was about 50°C above the ambient under maximum sunshine conditions. He calculated an overall efficiency of 30%.

Awachie (1982) used a solar hot box to dry fish, coconut, and maize. He obtained air temperatures of 40-50°C in the chamber during the wet seasons and above 50°C during the dry seasons. He reported that 0.74 kg of coconut lost 0.143 kg of moisture within 24 hours and that uncut fresh fish were fully dried in less than 72 hours, with about 50% of the moisture lost within the first 24 hours.

Arinze (1985) has successfully designed a commercial solar dryer for maize and other cereals that will be suitable for the northern part of Nigeria. Some states in the north are already using this dryer and others have placed orders for more.

Before 1980, some experimental solar dryers were tested at the universities of Nigeria, Nsukka, and Ife. In 1980, the design and evaluation was reported for a solar dryer with a reflector/concentrator type of collector in which shelled maize and sliced plantain were dried (Igbeka 1980). This dryer was also used to dry some other crops. Later, a flat-plate collector was used to heat air for drying maize on cob and sliced okra (Igbeka 1982) and this dryer was modified as a solar dryer/storage system by Araoye (1984) with very satisfactory results. In 1985, a solar dryer in which the crop being dried was also used as a heat absorber was designed and evaluated. The data and results of these three designs are reported here.

Evaluation of Three Types of Solar Dryers

Solar dryers available in Nigeria can be categorized into three types: concentrator/dryer, flat plate/dryer, and flat plate/dryer/storage unit. These may be passive or active systems but the work reported here was concerned with passive systems because they are more adaptable to rural areas. This study was conducted between the months of May and November.

Solar Concentrator/Dryer

The solar concentrator collector is not normally used for crop drying. However, it is evaluated here along with the other two dryers because it was the first collector built at Ibadan. The solar dryer is made up of a collector and a drying chamber (Fig. 2). The collector, which uses a stationary nontracking concentrator, was constructed from four reflective sheets of tin plate mounted on a parabolic frame structure with 3 cm of coconut fibre insulation between the plates and the frame. The frame structure was made from plywood (Igbeka 1980) and forms a parabola with a focal length of 25 cm. Other components of the collector include a black-painted aluminum pipe (145 cm long and 5 cm external diameter) fixed along the focal point of the parabolic mirror. The pipe is held concentrically within a glass tube (129 cm long and 8.8 cm diameter) with two wooden bungs. A transparent polyvinyl fluoride (PVF) film (0.15 cm thick) was used as the cover plate. With this arrangement, all rays normal to the surface of the mirror are reflected and concentrated on the black aluminum pipe. The parabola is tilted at 10° to the horizontal.

The drying section was constructed from 1.27-cm plywood and the sides are insulated with fibreglass. It is 48 x 48 x 123 cm including a plenum chamber 25 cm high where the aluminum pipe from the collector enters through a 5.3-cm hole. Above the plenum chamber is a false floor made of wire mesh. The drying chamber is constructed so that the dryer can be used both for tray drying and deep-bed drying and maize can be dried on-cob or shelled. The dryer was evaluated using shelled maize and sliced plantain. During field tests, chopped okra, sorghum, rice paddy, and maize on-cob were also used. This dryer was designated Dryer 1.

Flat-plate Collector/Dryer

The flat-plate collector/dryer is made up of a flat-plate collector (3.66 x 0.95 m) with glass cover and a drying chamber (1.06 x 0.54 x 0.76 m) made from plywood (Fig. 3). The absorber of the collector

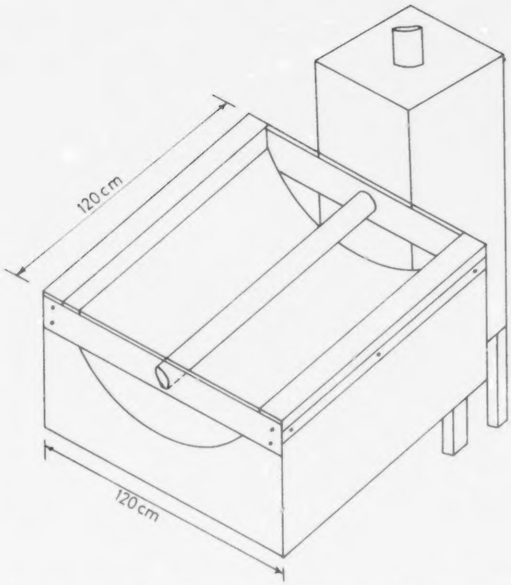

120 cm
120 cm

Fig. 2. Dimensions of the concentrator/dryer.

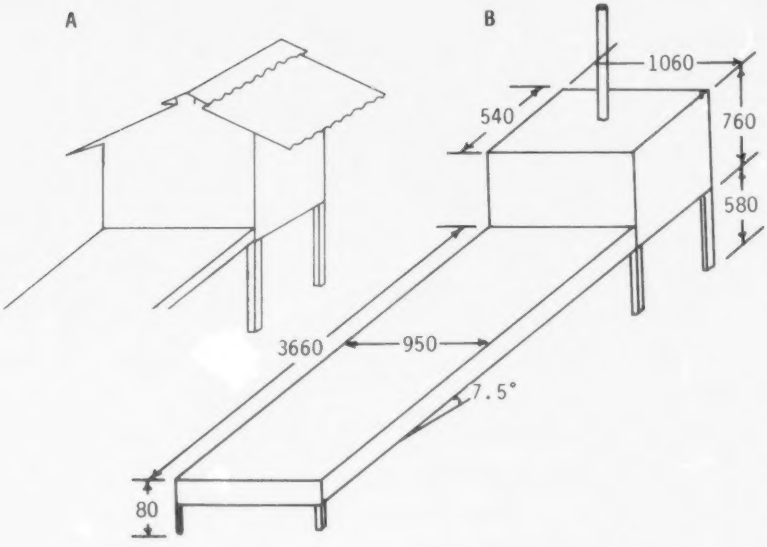

A
B
1060
540
760
580
3660
950
7.5°
80

Fig. 3. Flat-plate collector solar dryer: with in-bin storage (A) or drying chamber with chimney (B). (Dimensions in millimetres.)

is made of corrugated galvanized sheet that is painted black. The base and sides of the metal casing holding the plate are insulated with fibreglass of density 200 kg/m^3 and K of 0.038 W/m per °K. The sides of the drying chamber are also insulated with fibreglass.

The effective area of the collector is 3.22 m^2 and the cross-sectional area of the air passage is 0.0285 m^2. The dryer has a plenum chamber and a false floor made of wire mesh. The top of the dryer is covered with transparent corrugated sheet and has a chimney (50 cm long). This was designated Dryer 3. The dryer was evaluated with maize, either shelled or on-cob, sliced plantain, chopped okra, sorghum, and rice paddy.

Flat-plate Collector Dryer/Storage Unit

The collector for the dryer/storage unit is exactly the same as that for Dryer 3 and the drying bin is also of the same size and material. However, the roof is made of transparent corrugated plastic sheets fitted in a triangular cross section so that the apex has a sort of chimney effect (Fig. 3A). With this arrangement, the roof acts as a solar heat transmitter and the crop in the upper part of the bin also acts as a solar absorber. All other features are as in Dryer 3. This dryer was designated Dryer 2.

The dryer was evaluated with shelled maize, maize cobs, sliced plantain and yam, chopped okra, sorghum, and rice paddy.

Results and Discussion

Dryer Performance

The performance of the dryers was evaluated in two ways: drying rate, which is defined as the amount of water evaporated per unit absorbing area per day [$kg(H_2O)/m^2$ per day] and solar drying efficiency. The results of drying tests for three types of grains are presented in Figs 4 and 5. Also the drying curves for sliced plantain and shelled maize are given in Figs 6 and 7.

The solar drying efficiency, η, was defined as the ratio between the energy used for evaporating moisture out of the grain and the solar radiation against the absorbing area:

$$\eta = 100 \left[\int_0^t (M_w r/I)dt \right] \qquad [1]$$

where

M_w = drying rate [$kg(H_2O)/m^2$ per hour],

r = heat of vaporization of water out of the grain [W/hour per $kg(H_2O)$], and

I = solar radiation (W/hour per m^2)

The results are averages over a period of 6 months during which the minimum daily average radiation was 15.1 MJ/m^2 and maximum was

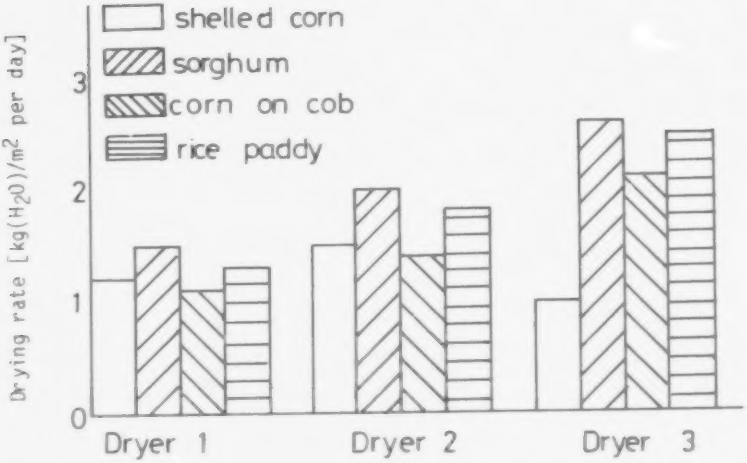


Fig. 4. Drying rates using the three dryers.

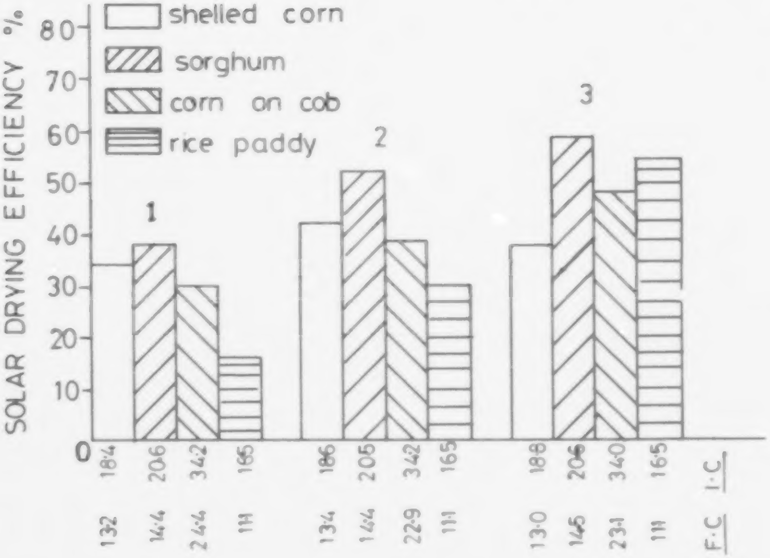


Fig. 5. Solar drying efficiency for three solar dryers: initial (IC) and final (FC) moisture content (% wet-basis).

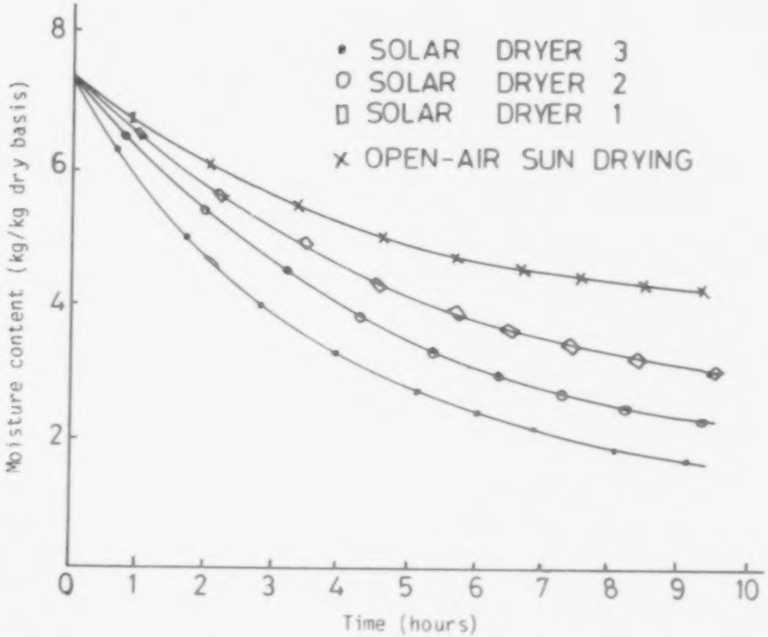


Fig. 6. Drying curves for plantain.

21.6 MJ/m^2. Dryers 2 and 3 were found to be more effective than Dryer 1. Although the air temperature difference recorded from collector 1 was the highest, the volume of air passing through it was far smaller than those of collectors 2 and 3. Therefore, the efficiency of collector 1 may be higher than the other two but its drying efficiency is lower.

The other results can be summarized as follows:

- For all three dryers, sorghum dried faster than the other grains (Fig. 4).
- There was not much difference between Dryers 2 and 3 especially for shelled corn but, for corn-on-cob and rice paddy, Dryer 3 is better (Fig. 4).
- Dryer 3 also gave the most rapid drying of plantain (Fig. 6), yam, and okra.

The better performance of Dryer 3 could be attributed to the better flow of heated air due to the chimney effect. It has been found that, in the absence of a fan, it is possible to obtain a substantial air movement through grain by creating a small pressure difference by the chimney effect. The pressure difference caused by the chimney effect can be described by:

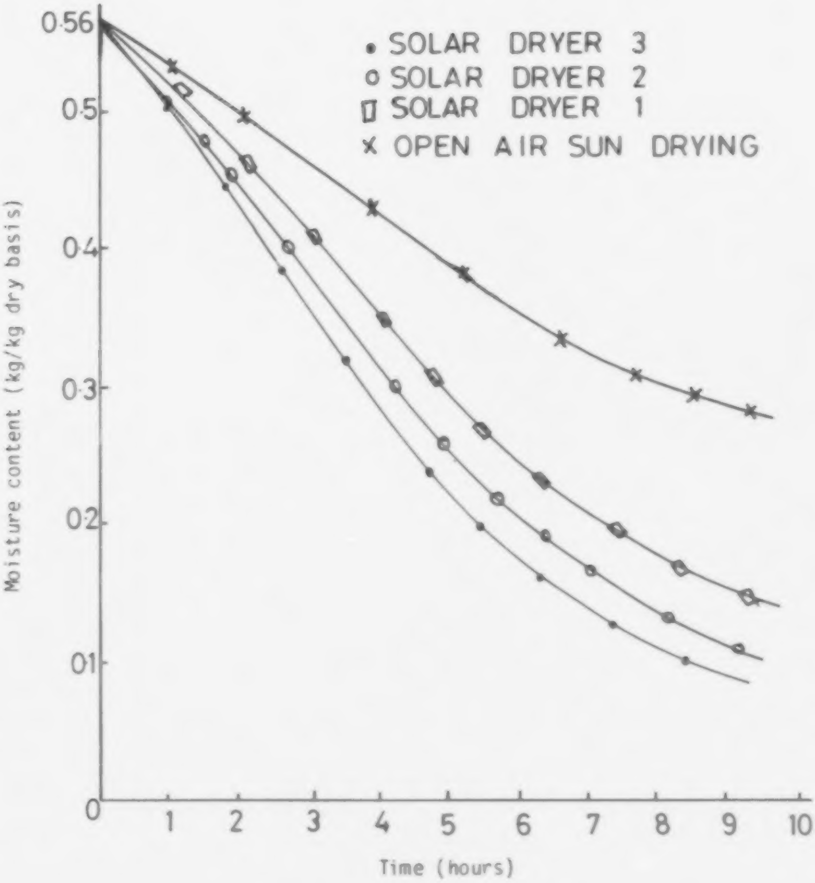


Fig. 7. Drying curves for maize.

$$\Delta P = \Delta\rho_{air}(gH) \qquad [2]$$

where

$\Delta\rho$ air = difference in density of the air inside and outside the drying chamber (kg/m^3),

g = gravity constant (m/s^2), and

H = vertical distance between the air inlet and outlet of the dryer (m).

The performance of Dryer 2 could, therefore, be improved by installing a chimney. This has already been suggested by the users and is being done in the modified version. The concentrator (Dryer 1) is not the best solar collector for drying but could perform very well for water heating. Because of the small volume of heated air coming in through the pipe, its effect is drastically reduced when it enters the much bigger plenum chamber of the dryer.

From the tests, it was observed and proved that, for passive solar grain dryers, which are most adaptable to rural farmers, the following parameters affect the drying capacity:

- Solar radiation;
- Type of grain, which will affect the airflow resistance, absorption of solar radiation, and moisture movement;
- Moisture content of the grain because moisture content at harvest affects the amount of moisture to be removed;
- Wind velocity;
- Height difference between the air inlet and outlet of the dryer (chimney effect); and
- Relative humidity of air, which depends on the climate or season. During the rainy season, the air is very humid and, even when it has been heated, the evaporative power of the air stream is still low. In fact, the air may be adding moisture instead of removing it. During this period, the use of dessicant is recommended.

Field Tests and Customers' Reaction

These three types of solar dryers have been demonstrated in agricultural shows and Technology Week exhibitions to farmers and the public. During these demonstrations, grains and food products such as plantain, yam, and okra were dried. The people were asked to give their opinion of choice among the dryers and to make critical analysis. A total of 210 people responded. Some of the questions were:

- What is your level of farming (small, medium, or large) and what types of crops do you produce?
- What type of drying and storage systems do you use now? If none, do you want to adopt one? If you have one, do you want to change for a solar type?
- If you were to adopt a solar dryer, which of the three would you choose? Give reasons.
- If you do not want to adopt a solar dryer, give your reasons.

From the reactions of the farmers and other people, three main conclusions could be drawn.

First, most of the small-scale farmers did not have any artificial drying system and their drying was done in the open sun. Some of the medium-scale and all of the large-scale farmers had some sort of artificial drying and storage systems.

Second, the medium-scale farmers preferred either Dryer 2 or 3 whereas the small-scale farmers preferred Dryer 3, which is a batch dryer and could be used for different crops instead of the dryer-storage system (Dryer 2), which would be tied to one type of crop.

Third, most of the rural farmers noted that their reservations in adopting a solar-drying system were due to lack of skill for maintenance and the initial cost, a miminum of USD 500. They believed that the equipment needed much skill to operate and maintain. Most of them had not seen the solar dryer physically but only in newspapers and televisions. This showed that the testing or extension procedure was not adequate.

Recommendations and Conclusions

A substantial amount of work has been done in the application of solar energy to agriculture in Nigeria, especially for food drying, the results of this work have not been used productively by the rural farmers. This is due to lack of coordination between the workers and researchers and also due to inadequate extension of the results to the farmers.

It has been found that the Nigerian farmer has no sociocultural inhibition to using solar dryers but will readily accept a design that is maintenance-free and inexpensive to buy.

On this basis, the following six recommendations are made to help achieve the objectives of getting solar dryers to the rural farmers in Nigeria.

First, solar dryers designed for the Nigerian rural farmers should be cheap, easy to maintain, and easy to use for drying any of the tropical crops. To achieve this, local materials should be used.

Second, there should be coordination between researchers and workers in the areas of solar drying in the country. A good forum is the Solar Energy Society of Nigeria and some coordination is already being achieved through its annual conference.

Third, because of the differences in the climatic zones in Nigeria, it might be necessary to zone the country for the purposes of solar-drying research. The north is dry almost throughout the year but the humidity in the south is quite high for more than 4 months. Therefore, the use of dessicants in the humid south should be investigated: some local dessicants, for example, granular wood ash, are available.

Fourth, the best design, which is recommended for Nigerian rural farmers, is the flat-plate collector/dryer with transparent roof. The roof, which should be double-pitched, acts as an insolator. Depending on the available funds, the transparent covering of the collector could be made from glass, plastic, or polyethylene. To improve the performance of this dryer, a chimney should be installed.

Fifth, the design of the drying chamber should permit the farmer to use it as a tray dryer or as an in-bin storage dryer.

Sixth, funds should be made available for research into the effect of size on the performance of solar dryers. At present, the designs have been limited to small-capacity collector/dryers. Also, funds should be made available for research into use of local materials to reduce the cost of the solar dryer.

References

Adebiyi, G.A. 1982. Design, construction and testing of a solar steam unit. Nigerian Journal of Solar Energy, 2, 69-73.

Araoye, A.O. 1984. Design, fabrication and testing of a solar dryer. University of Ibadan, Ibadan, Nigeria. BSc project report.

Arinze, E.A. 1982. Instantaneous, hourly and daily prediction of incident and transmitted solar radiation on a double-layered plastic covered tiled surface. Nigerian Journal of Solar Energy, 2, 15-25.

———————— 1985. Design and performance evaluations of large-scale natural convection solar crop dryer. In Proceedings of National Solar Energy Conference, Enugu. Solar Energy Society of Nigeria.

Awachie, I.R.N. 1982. Design features and test results of a solar hot box. Nigerian Journal of Solar Energy, 2, 74-80.

Bamiro, O.A. 1983. Empirical relations for the determination of solar radiation in Ibadan, Nigeria. Solar Energy, 31(1), 85-94.

Bamiro, O.A., Ideriah, F.J.K. 1982. Determination of the optimum collector orientation for Ibadan, Nigeria. Nigerian Journal of Solar Energy, 2, 26-32.

Chendo, M.A.C., Schmitter, E.F. 1982. Observed performance of Perspex covered solar still. Nigerian Journal of Solar Energy, 2, 26-46.

Doyle, M.D.C. 1982. The estimation of diffuse solar radiation. Nigerian Journal of Solar Energy, 2, 3-14.

Ezeilo, C.C.O. 1979. Angular space-time relations in solar radiation. Nigerian Journal of Technology (NIJOTECH), 3(1), 35-45.

Ezekwe, C.I., Ezeilo, C.C.O. 1981. Measured solar radiation in a Nigerian environment compared with predicted data. Solar Energy, 28, 181-186.

Ideriah, F.J.K. 1981. A model for calculating direct and diffuse solar radiation. Solar Energy, 26(5), 447-452.

Ideriah, F.J.K., Bamiro, O.A. 1982. The determination of diffuse component of solar radiation in Ibadan. Nigerian Journal of Solar Energy, 2, 81-88.

Igbeka, J.C. 1980. Solar energy utilization for rural agriculture (poster presentation). In Janzen, A.F., Swartman, R.K., ed., Solar energy conversion II: International Symposium on Solar Energy Utilization, London, Ontario, 10-24 August 1980.

__________ 1982. Flat plate solar collector/dryer. Department of Agricultural Engineering, University of Ibadan, Ibadan, Nigeria. Unpublished research report. 28 pp.

Ofi, O. 1982. Construction and evaluation of a solar dryer. Nigerian Journal of Solar Energy, 2, 47-59.

Tani, E.D. 1979. Design and development of a photovoltaic energy system as an alternative for the rural tropical habitat. Department of Agricultural Engineering, University of Ibadan, Ibadan, Nigeria. MSc project report.

APPROPRIATE TECHNOLOGY FOR SOLAR FISH DRYING IN ARTISANAL FISHING CENTRES

Niokhor Diouf[1]

Abstract -- *An overview is presented of the improvements in the artisanal manufacturing technology chain for various types of dried fish using simple polyethylene solar dryers and appropriate techniques for pretreatment and preservation after processing. The paper also attempts to answer the question: is solar drying economical for local producers and consumers of dried fish? This question is particularly relevant because natural drying, notwithstanding the favourable climatic conditions, has resulted in some loss of productivity by the processors.*

Analysis of Technical and Socioeconomic Aspects of the Artisanal Fish-Processing Sector

Improvement of suitable technologies for the rural and urban communities is a priority in developing Africa. This priority has been clearly recognized by the Institut de technologie alimentaire, which, together with the Food and Agricultural Organization of the United Nations (FAO) and the U.S. Agency for International Aid (USAID), has sought ways of adapting solar drying to local production of dried fish in the artisanal fishing centres of Senegal and Gambia.

The artisanal fish-processing sector (Table 1) offers thousands of jobs and considerable revenues. The processor has become a true business person employing 3-5 people, or more, according to need, to gather fresh supplies of raw materials, to preprocess the fresh fish, monitor the drying operations, and package and market the finished product.

The processing and storage operations for dried fish are simple and basic. The work is performed with bare hands, often directly on the ground, using simple instruments that are barely in fit condition. The processing area is polluted[2] and the processors have no respect for basic hygiene and cleanliness. They also use a number of insecticides, particularly DDT and Propuxor, to protect the product from infestation. In addition, the processors experience many acute problems in marketing dried fish even though demand exceeds supply both locally and on the African continent as a whole.

---

[1] Institut de technologie alimentaire, Dakar, Senegal.

[2] The pollution is due especially to fishing or production wastes, which permit insect pests that infest the dried fish to breed, and to the waste waters and refuse of all kinds that litter the ground.

Table 1. Fish processed artisanally in Senegal, 1977-1983.

End product	Quantity produced (t/year)						
	1977	1978	1979	1980	1981	1982	1983
Dried salt fish (*saly*)	953	988	707	758	528	477	640
Dried braised fish (*kéthiakh*)	7169	6002	5728	6014	7047	6458	7950
Smoked fish (*métorah*)	1387	1381	1027	698	680	657	560
Dried fermented fish (*guédj*)	3869	4232	3751	3403	3496	3436	3688
Whole dried fish (*tambadiang*)	3017	2894	3338	3928	939	713	3950
Toufa, *yeet*	1632	3580	5200	7403	2803	1567	925
Other end products (*pagne*, *yokhoss*)	1794	112	97	132	2272	4000	105
Total end products	19821	19189	19848	22336	17765	17308	17818

Source: Oceanographic and Maritime Fishing Service.

Note: The fraction of total end products of fish processed by artisanal processors varies between 30 and 60% when the full range of raw materials and processes is taken into account. Artisanal processing accounts for 45,000-60,000 t of fresh fish annually, including the amount consumed personally by the artisans.

In parallel with the development of artisanal fishing, artisanal processing has shifted from direct, consumption-oriented production to trade-oriented commercial production. However, the technology of dried-fish production has stagnated somewhat since 1960 following a governmental order prohibiting natural drying on the ground in the concessions in favour of natural drying on racks at the landing sites.

Two major attempts, 20 years apart, to improve dried-fish production were unsuccessful, at Saint-Louis and MBour. There were other unsuccessful attempts to introduce mechanical fish-drying factories in the fishing centres that were rich in high-demand species, notably at Kayar, despite the application of scarce resources (investment capital, currency, and energy).

Applied research on fish technology in the fishing centres has given relatively poor results, in particular because all the research and development (R&D) projects have focused, and still focus, on particular techniques to the detriment of an overall study of the improvements that are needed in the field of production of each type of dried fish. Thus, nature still exerts a predominant influence on the various techniques for producing dried fish. Operations to prepare the fish before drying are undertaken directly on the ground, and the natural heat of the sun is used for drying. The salt used is manufactured in an artisanal fashion by drying out salt lakes. The drying racks are made of wood, and reeds and palmyra creepers are used for wrapping fresh or dried fish.

After examining the present technological situation in dried-fish production in the artisanal fishing centres, it is clear that an integrated approach is needed to remedy the various technical, social, and economic deficiencies. This great vital sector could then enjoy a harmonious and integrated development.

Equipment and Methods

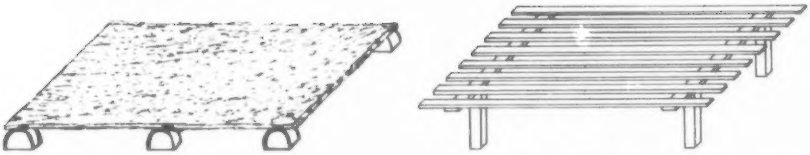
This study started during the phase of adapting solar dryers to the local conditions of dried fish production and proceeded with the installation of solar drying facilities in the fishing centres of MBour, Joal, Kayar, and Missirah.

Apart from the operations of scaling, gutting, and washing, the preparation of fresh fish for open-air drying (Fig. 1) or for drying in a solar enclosure includes various operations depending on the nature of the final product: kéthiakh (Fig. 2), guèdj (Fig. 3), saly (Fig. 4), and tambadiang (Fig. 5).

Each solar drying workshop (Fig. 6) has the appropriate equipment for producing these four types of dried fish. The preprocessed fish is dried in two ways: static drying on artisanal or improved racks (Fig. 1) and in Brace-type (Fig. 7) or house-type (Fig. 8) solar dryers; or drying by hanging in the dome dryer (Fig. 9).

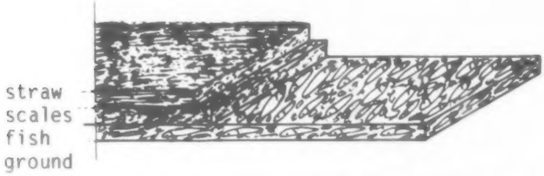
Operation of Polyethylene Solar Dryers

These three polyethylene solar dryers are direct heating systems that use only solar energy and in which the fish to be dried acts as the absorber. The frame is made from metal for the dome dryer and

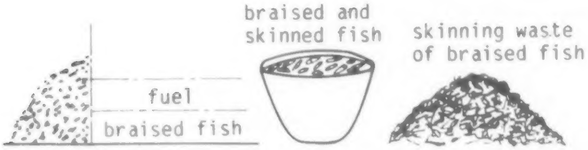


A. Artisanal drying rack B. Improved drying rack

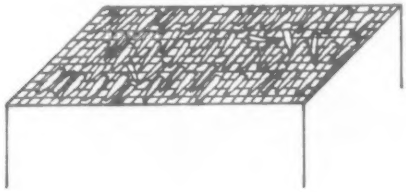
Fig. 1. Fish drying racks.


straw
scales
fish
ground

A. Before braising: preparation technique


braised and skinned fish
skinning waste of braised fish
fuel
braised fish

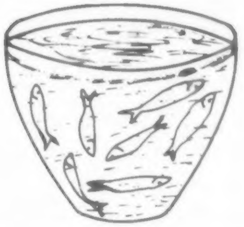
B. After braising: handling of braised fish



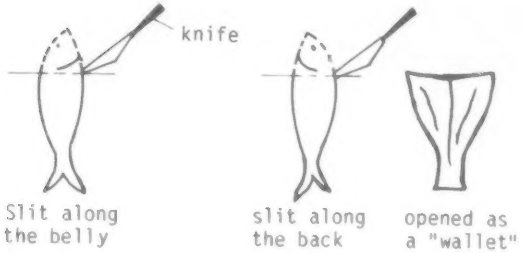
C. Natural drying of braised fish

Fig. 2. Artisanal technique for preparing kéthiakh (braised dried fish).

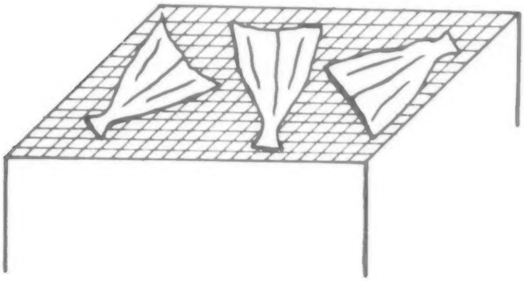
from wood for the other two. Solar radiation passes through the clear faces (transparent polyethylene of 180 μm) of the chamber but is absorbed by the blackened faces (black polyethylene of 300-350 μm).



A. Fermentation of whole fish in brine



B. Preparation of fermented fish

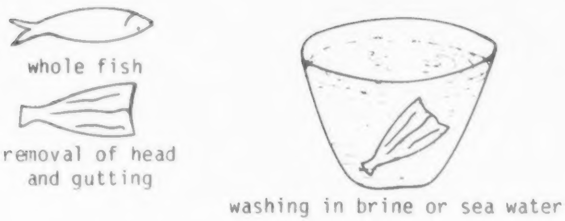


C. Drying fermented fish on a rack

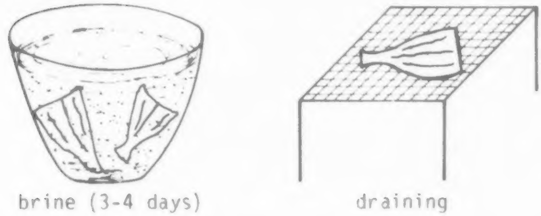
Fig. 3. Technique of preparing guédj (dried fermented fish).

Drying air circulates as a result of vents above and below the installation. A door allows access by the processors. The site of the solar dryer installation must be well exposed to the sun all day, and the openings of the lower vents must be oriented toward the prevailing winds.

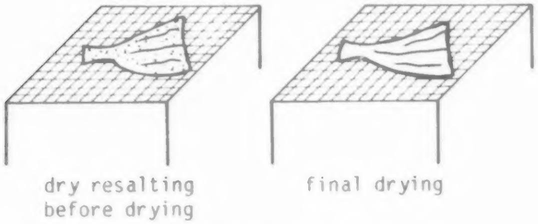
Solar radiation enters the installation through the transmissive surfaces and is then absorbed in the form of heat by the internal blackened surfaces. In turn, these blackened surfaces reemit radiation mainly in the infrared region, only a small part of which escapes


whole fish
removal of head and gutting
washing in brine or sea water

A. Preparation of fish before salting


brine (3-4 days)
draining

B. Salting of prepared fish


dry resalting before drying
final drying

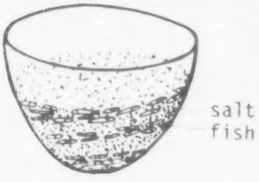
C. Drying of salt fish

Fig. 4. Artisanal technique for preparing saly (dried salt fish).

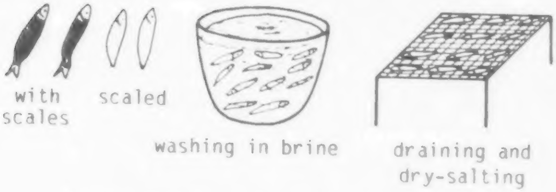
through the transparent surfaces. Heat is, therefore, trapped through the greenhouse effect and is transmitted to the drying air by conduction and radiation, but mainly by convection. The heated air expands in the drying chamber, becomes laden with humidity from the product, and escapes through the air outlet. The lower air inlet allows the drying air to be replaced as it rises and escapes from the dryer.

The supports used in rack fish drying operations cover all of the floor except for the part used as a walkway by the processors. These racks have an openwork structure to allow the drying air to pass through. The product to be dried is distributed uniformly along the rack, with small regular spaces left so that it can be turned over periodically. In this way, the degree of drying can be controlled.

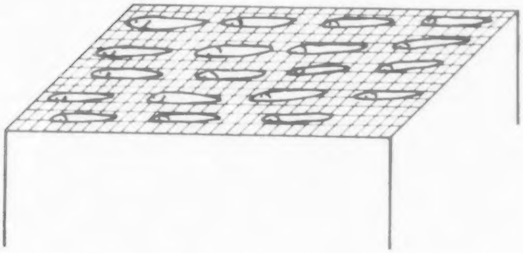
The air vents are closed at night, or whenever rain threatens, to avoid any significant re-wetting of the product.



A. Fermentation of whole fish



B. Preparation of semifermented fish



C. Drying of whole semifermented fish

Fig. 5. Artisanal technique for preparing tambadian (whole dried fish).

Monitoring of Drying

To monitor the kinetics of drying and the changes that take place in fish quality during the preprocessing and the natural and solar drying phases, we measured the physical characteristics of the drying air using Ultrakurst telethermometers to measure temperature, Richard hygrometers to measure relative humidity, and anemometers to measure the airflow. Water activity was measured with the Aw-Value analyzer Model 5803. We analyzed the weight loss of the product during production and the changes in the chemical, microbiological, and organoleptic quality of both the product to be dried and the finished product.

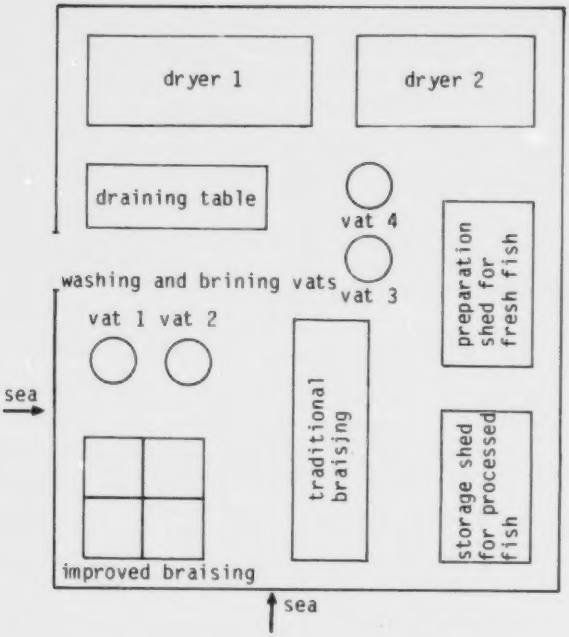

dryer 1
dryer 2
draining table
vat 4
vat 3
preparation shed for fresh fish
washing and brining vats
vat 1 vat 2
sea
traditional braising
storage shed for processed fish
improved braising
sea

Fig. 6. Model solar dryer workshop at the Institut de technologie alimentaire, Senegal.

Results and Discussion

Preparation of Fish before Drying

Braising the pelagic species (gilt sardine and Ethmalosa finbriata) in a breezeblock oven (80-90 x 10^2 kcal/kg of fish) is more hygienic and reduces smoke production considerably. In addition, the moisture content of the fish drops by 9-15% during braising in an oven, compared with 5-10% during braising on the ground. This is equivalent to lowering the water activity from about 0.99 to 0.91 for fish braised on the ground and to 0.84 for the fish braised in an oven. Irrespective of the method of braising, the braised fish is cooked.

Fermentation of the fish whole, or gutted together with the guts, in vats of light brine (6-12° Beaumé) under good hygienic conditions produces a fermented product whose taste, appearance, and aroma are sought by the processors. In addition, the lactic flora of fermentation develops rapidly and reaches a stable level of 10^5-10^6, in contrast to the microbial flora of putrefaction that decreases appreciably. It should be noted that the Lactobacillus plantarum has a prominent influence on quality as well as quantity in the process of fermenting guédj.

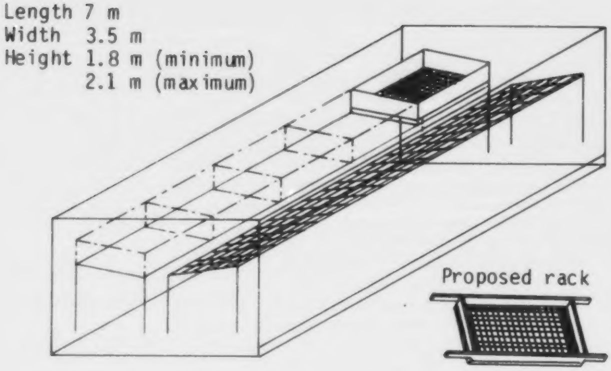

Length 7 m
Width 3.5 m
Height 1.8 m (minimum)
2.1 m (maximum)
Proposed rack

Fig. 7. Drying racks in the Brace-type solar dryer.

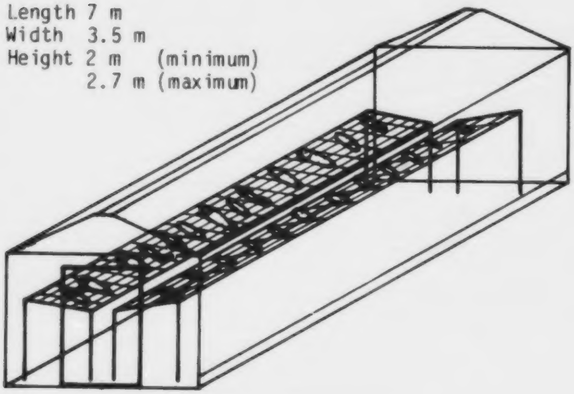

Length 7 m
Width 3.5 m
Height 2 m (minimum)
2.7 m (maximum)

Fig. 8. Solar house dryer.

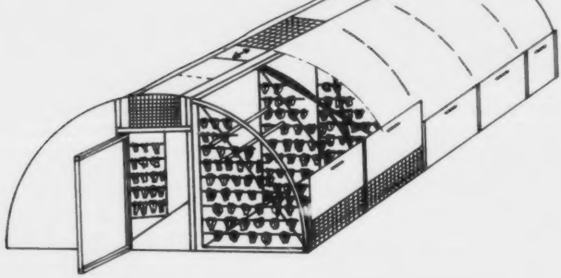


Fig. 9. Solar dome dryer with hanging fish.

Dehydration of fresh fish in dry salt is faster than in brine. For instance, after about 48 hours, the water activity of the Nile perch reaches about 0.85 in dry salt, compared with 0.90 in brine. However, the processors use a combination of dry salting and brining because the salting vats are not designed to allow the water exuded by the fish to drain off simultaneously. Deterioration of salt fish can be prevented by taking two precautions: avoiding trimming the fresh fish on the ground before salting to eliminate possible deterioration of the salt fish by moulds, and using salt that is free from hallophilic bacteria for salting by storing marine salt for 6-7 months before using it.

The preparation phase of fresh fish before drying is important because it allows, among other things, the temperature adjustment phase to be shortened. In addition, preprocessing the fish by salting or braising before drying increases the efficiency of the drying operation and results in products that match the particular tastes of the consumers.

Physical Characteristics of Drying Air

Between February and June at MBour and Joal, the temperature inside the dryers varies during the hours of sunshine between a maximum of 53°C and a minimum of 28°C (Fig. 10). Between 1200 and 1600 hours, the temperature is about 49-53°C. Relative humidity (RH) inside the dryers varies between 84 and 33%, with a level of 33-38% between 1200 hours and 1600 hours. Ambient temperature varies between 37 and 28°C without leveling off, and the atmospheric RH varies between 84 and 55%, again without leveling off. In addition, the circulation of the drying air in the dryer through natural convection is appreciable and amounts to about 25% of the speed of the ambient air (Table 2).

Mean daily total insolation measured with a solarimeter equipped with an integrator (Lintronic Ltd, 54-59 Bartholemew Close, London, U.K.) was about 15 MJ/m^2.

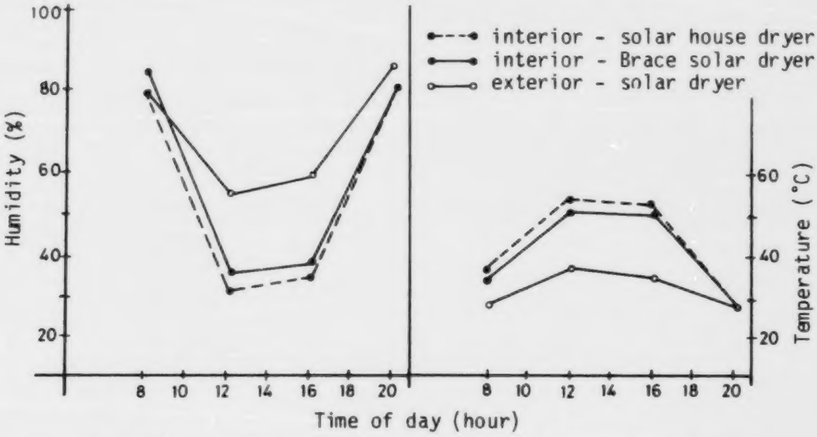


Fig. 10. Diagram of relative humidity and temperature inside and outside the solar dryers.

Table 2. Measurements of drying air speed.

Time of day (hour)	Ambient wind speed (m/sec)	Air speed in dryer (m/sec)	
		Inlet	Outlet
800	3.90	3.05	0.90
1200	3.20	2.88	0.80
1600	4.54	3.90	1.20
1800	3.80	2.87	0.86

Use of the solar dryer under these various conditions of temperature, RH, and drying air circulation make solar drying noticeably superior to artisanal drying. The effects of climatic conditions are less harmful than those for natural drying because the dryer is enclosed -- fish dried naturally are contaminated by atmospheric dust, which is intense in the dry season in the Sahel, and are rewetted by nocturnal humidity and rainfall. Losses due to larvae and larder beetles, which can be seen on the artisanal racks, are eliminated. Infestation by these insects is particularly intense during the rainy season.

Despite these clear advantages, the solar dryer remains subject to frequent variations of atmospheric air characteristics and solar intensity. This raises the question of how to "free" the solar dryer from variations in atmospheric conditions, as is the case for the heat pump.

Differences between Fish Dried Artisanally and in the Solar Dryer

Braised Fish

Predrying of the fish and temperature adjustment are partially or entirely completed during the braising operation (Table 3), according to the intensity of the fire. Thus, removal of surface water from the braised fish is completed after about the first 4-5 hours of exposure in the dryer (Fig. 11A). The accelerated solar drying phase for braised fish lasts about 30 hours (i.e., 18 hours of effective drying) after which the kéthiakh has a moisture content less than 28%, as opposed to more than 32% humidity for fish braised and dried on racks for about 45 hours or more. Interruption of drying during the night is beneficial because residual water migrates from inside the fish to the surface. This explains the marked improvement in the drying of braised fish during the first hours of the morning. However, this phenomenon becomes complicated for fish braised and dried on racks due to the amount of nocturnal condensation. Oven-braised fish dries more rapidly without salt in the dryer (about 14 hours of effective solar drying) than lightly salted fish braised on the ground (about 18 hours of effective solar drying). The temperatures reached in the solar dryer do not degrade either the colour or the taste of the kéthiakh produced. In addition, the final product has a firmer flesh, a much appreciated taste, a better appearance, and an almost total absence of the odour which characterizes artisanally dried kéthiakh.

Table 3. Fish quality during solar drying of kéthiakh and guédj.

Product	Protein (%)	Total nitrogen (mg/100 g)	pH	Humidity (%)	Water activity	Flora			
						Aerobic	Putrid	Lactic	Hallophilic
Kéthiakh									
Fresh fish	21.9	24	5.95	65.7	0.99	1×10^5	<10	-	-
Braised fish	29.6	26	6.05	58.0	0.89	3×10^4	<10	<10	<10
Dried braised fish	62.0	27	6.20	24.0	0.70	4×10^4	<10	<100	<100
Guédj									
Fresh fish	18	35	6.30	72	0.98	6×10^5	10^2	<10	-
Fermented fish	23	60	6.70	68	0.94	5×10^6	<10	10^5	10^2
Dried fermented fish	59	58	6.72	28	0.75	4×10^5	<10	10^3	10^3

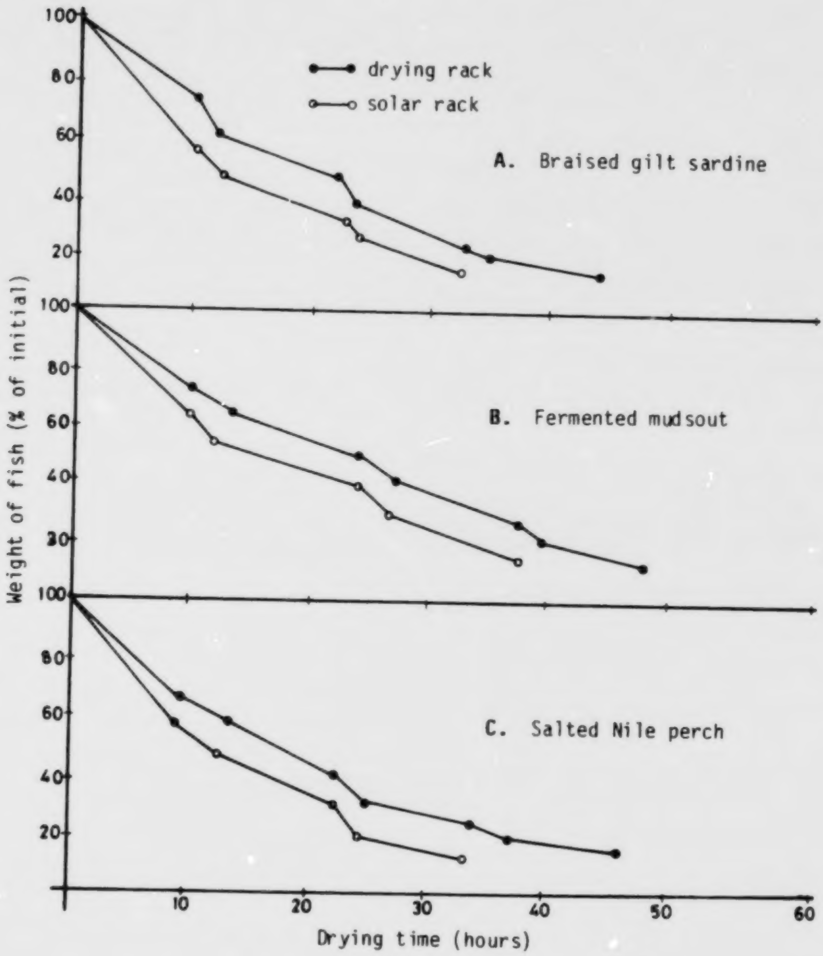


Fig. 11. Drying curves for braised (A), fermented (B), and salt (C) fish.

Fermented Fish

Solar pre-drying of fermented and trimmed fish for 4-5 hours with the access door open is necessary to avoid the formation of a crust on the surface of the product. To prevent crust formation on the surface of the fermented fish, drying temperatures should be below 42°C and drying air speed greater than 1 m/sec.

Loss of surface water from the fermented fish continues for about 8 hours, which coincides generally with the 1st day of solar drying.

By this time, the moisture content of the half-dried fermented fish is between 46 and 56% (Fig. 11B). During the following night, water migrates from the inside of the product to the surface and this occurs more rapidly if nocturnal condensation in the dryer is minimal. If fine salt is scattered on the slab, nocturnal condensation and rewetting have a negligible effect on the product and, the following day, the product surface is moist due only to migration of water from the inside of the fish to the surface.

The accelerated solar drying phase lasts about 10-20 hours depending on the type and thickness of the fermented fish. Migration residual water from the interior of the product accelerates drying during the early hours of the morning. This also accelerates the process of fermentation of the product, whose bacterial and lactic flora contents increase to stabilize at between 10^5 and 10^6 each night (Table 3).

The temperatures during accelerated drying of the fermented fish must not exceed 50°C to avoid degradation of the colour and taste of the final product.

Fermented fish cannot be dried by hanging in the dome dryer because it generally falls onto the slab before the end of drying, thus degrading the appearance of the final product.

Fish fermented and dried in the solar dryer (27-30% humidity after 32-38 hours) is much appreciated and has a good appearance, colour, and taste, as well as being less acidic than the guédj obtained by natural drying.

Salted Fish

Study of solar drying of salt fish is an on-going activity. The results obtained so far nevertheless indicate that solar drying accelerates the drying process (Fig. 11C) without recourse to conventional energy sources, solves the problem of infestation of drying or dried fish by insects, and yields a final product of better chemical, microbiological, and organoleptic quality.

The polyethylene solar dryer has some limitations:

- The solar dryer depends on the surrounding atmospheric conditions, even though, in contrast to the artisanal rack, the product is directly protected against the negative effects of nature.
- The dryer construction cost is high compared with the cost of an artisanal drying rack.
- The transparent polyethylene tears easily and must be replaced after each year of use.
- Processing capacity is inadequate according to the processors if the dryer is equipped with only one layer of drying racks.

Nevertheless, our investigations to improve the technical qualities of polyethylene dryers continue. Thus, to increase drying capacities, the dimensions of the access doors must be increased to allow drying racks (see Fig. 7, proposed rack) to be filled with fish outside and piled five to seven deep.

General Characteristics of Solar Drying Operations

The fish-processing community has rapidly assimilated the technological innovations for producing dried fish in the workshops, which are described in Appendix 1. These processors are producing all the types of fish dried in Senegal, depending on the availability of raw materials and customer demand, despite their previous specialization in only one product.

The use of preprocessing and solar drying structures in the facilities has resulted in rationalization of the production technology for the various types of dried fish. Dried fish production was characterized, among other things, by savings in drying time (1-2 days on average according to the size of the species and the needs of the customers) and in braising fuel.

Whatever type of fish is dried, the total production expenses cover the purchase of the raw materials (about 65-82% of the amount spent) and overheads. The cost of raw materials and overheads vary according to the types of fish dried and the fishing centres. The acquisition costs of raw materials can double depending on market fluctuations (Table 4).

Three channels are used to sell plant production:

- Direct sale to the wholesale fish merchants (intermediates between processors and consumers) who, because of their considerable financial resources, set the buying price from the processors;
- Sale in the major dry-fish marketing centres where the processors take their merchandise using rented vehicles; and
- Sale to the dried-fish exporters at a price negotiated at the time of signing the contract, which is prepared before production starts.

The last two forms of marketing the product are favoured by the processors who earn substantial profits in contrast to the first form where they can make either profits or losses according to the traditional laws of supply and demand.

Prospects and Recommendations

After a few months of operation of the facilities, the benefits are numerous and diverse. The following recommendations address the problems that still remain:

- Increase the drying capacity of each dryer by drying preprocessed fish in stacks of five to seven piled drying racks (Fig. 7);
- Improve the conditions for supply of raw materials to the processors (more precisely, equip the facility with isothermal containers for preserving fresh fish on ice) and, most

Table 4. Analysis of production costs of *kéthiakh* in Joal workshop (1 week of production)

	Costs (XOF x 10^3)[a]	Cost of production (%)
Production costs		
Raw materials (4 baskets of fish)	55.0	80.41
Products required for production		
Wood	4.5	
Salt	1.1	
Total	5.6	8.19
Labour cost		
Delivery of fresh fish in handcarts	4.0	
Oven loading	1.3	
Scaling of braised fish	2.0	
Lighting costs	0.5	
Total	7.8	11.40
Turnover at Joal[b]		
Total sales	124.2	
Profit	55.8	
Turnover in marketing centres[b]		
Cost of vehicle rental	27.8	
Cost of wrapping and sales	28.0	
Total costs	55.8	
Total sales[c]	224.2	
Profit	100.0	

[a] In 1986, 220 XOF (franc of the Communauté financière africaine) = 1.00 CAD (Canadian dollar).

[b] Total weight of *kéthiakh* = 1180 kg.

[c] The cost of *kéthiakh* made by braising on the ground was between 40 and 70 XOF/kg at Joal at the time when *kéthiakh* braised in the oven cost 90-130 XOF/kg. The *kéthiakh* is sold at 190 XOF/kg in most of the major marketing centres.

importantly, regularize plant production by having a minimum daily quantity of raw materials available;

- Improve the production and marketing of products by maintaining a staff of experts to promote the following aspects: team spirit; cooperative endeavours; credit structures; and business management and marketing;

- Improve production hygiene by taking the following actions: pave the inner yard to reduce the reproduction of destructive insects; recover the value from waste and by-products of processing; use cleaner water in the operations; and illuminate the plant with gas lamps so that the processors can work on the nightly arrivals of fresh fish in good and safe conditions;
- Improve the storage conditions of dried fish before marketing to minimize the qualitative and quantitative losses of the product due to insects and rewetting, particularly at night;
- Continue studies on the technological chain of production for dried fish, especially the fish fermentation process and the interplay between salting and drying; and
- Continue studies on the innovative and investment capacities of the processors by in-depth examination of the possibilities of subsidies or credit systems for processors.

Conclusion

Implementation and operation of solar drying facilities by fishery technologists and experienced processors represents real progress in applied research on artisanal fish technology in Senegal. That collaboration between technologists and processors has set a good example is shown by the activities of the processors. The processors have contributed greatly to better adapting these technological innovations to the local conditions of the fishing centres. Thus, these workshops allowed us to introduce team work into the corporate processor community, despite the individualistic character that predominates in that sector; to produce good quality dried fish in conditions of good hygiene; to initiate a study of rationalization of the artisanal dried-fish production chain; and to identify the other technical and socioeconomic problems that must be solved to accompany the introduction of solar dryers in the fishing centres.

The key thing is to continue working toward the improvement of solar fish drying. Close collaboration between scientists and processors can only be beneficial, because the processors demonstrate a potential for creativity and initiative that can help develop a more effective and less costly solar drying technology.

References

Diouf, N. 1986. Les techniques artisanales et modernes de préparation du poisson séché et fumé. Séminaire de perfectionnement FAO/DANIDA et technologie et contrôle de qualité du poisson, 2 juin au 4 juillet 1986. Institut de technologie alimentaire, Dakar, Senegal.

Diouf, N., et al. 1983. Le séchage solaire du poisson. Institut de technologie alimentaire, Dakar, Senegal. Technical Report 3, 1982.

Diouf, N., et al. 1984. Construction et exploitation de quatre ateliers de séchage solaire à MBour, Joal, Missirah et Kayar:

Bilan (juillet 1983 - 31 mai 1984) et perspectives. Institut de technologie alimentaire, Dakar, Senegal.

Diouf, N., Sarr, M. 1982. Le séchage solaire du poisson. FAO Conference of Experts on Fish Technologies in Africa, Casablanca, Morocco. FAO, Rome, Italy.

Durand, M.M., Conway, J. 1982. La transformation artisanale, son rôle dans l'écoulement des produits de la mer au Sénégal. FAO Conference of Experts on Fish Technologies in Africa, Casablanca, Morocco. FAO, Rome, Italy.

Sainclivier, M. 1985. L'industrie alimentiare halieutique : Volume 2 -- des techniques ancestrales à leurs réalisations contemporaines. Sciences Agronomiques, Université de Rennes, France.

Appendix 1: Solar Drying Workshops

A group of six processors operate the workshop with the training assistance and supervision of a fish technologist from the Institut de technologie alimentaire. The work consists essentially of purchasing raw materials, preprocessing and drying the fish, and then selling the final product. The processors receive 80% of the value of sales of the finished product. Facility maintenance and operating costs (Table 5) account for 20% of the receipts.

Table 5. Cost of establishing the workshop and estimated monthly depreciation

Equipment	**Total cost (XOF)**[a]	**Useful life (years)**	**Monthly depreciation (XOF)**
Solar dryers (racks, frame, slabs)	280,000	4	5,834
Braising oven	76,000	4	1,584
Fermentation, salting, and washing vats	40,000	4	834
Handling shed	40,000	3	1,112
Storage shed	40,000	3	1,112
Fence	26,000	3	695
Clear polyethylene	60,000	1.25	4,000
Small equipment (knives, basins, lamps)	24,000	1	2,000
Total			17,171

Note: Workshop processing capacity
500 kg of fresh fish per fermentation, washing, and salting vat
600-750 kg of gilt sardine and *Ethmalosa finbriata* per braising oven
600-750 kg of mudsout and Nile perch per braising oven.

Capacity of solar dryer facility:
1 t/2 days with single layer drying racks or
2 t/2 days on average with double layer racks.

Drying time for preprocessed fish:
1-2 days depending on processor and priorities.

[a] In 1986, 220 XOF (franc of the Communauté financière africaine) = 1.00 CAD (Canadian dollar).

SOME RESULTS FROM SOLAR DRYING TESTS AT THE CENTRE NATIONAL DE RECHERCHES AGRONOMIQUES

Hyacinthe Modou Mbengue[1]

Abstract — *In Senegal, most of the cereal harvest is dried in the field, apart from a small portion which is intended for immediate domestic consumption. Various methods are used for drying unthreshed grain in the field. In some cases, entire plants are cut at harvest and sun-dried directly on the ground. In other cases, the ears are cut and piled in bulk or tied in sheaves of about 10 kg, and left to dry in large heaps on the ground. When this is done, during the 5-6 weeks of drying, the exposed grain may be attacked by rodents, insects, and birds, even though the grain is sometimes wrapped with thorny branches. The aim of this research was to test new dryer prototypes that could improve grain drying, especially sorghum. Tests were conducted using a natural convection crib-dryer and four prototype dryers equipped with solar collectors. The crib-dryer is of particular interest because it affords a more efficient way of drying and storage than the traditional methods used by the farmers. To warrant the purchase of such a dryer purely on the basis of economics, it must be able to reduce losses directly by 14.3%. The secondary advantages, such as freeing parcels of land and better distribution of harvest for mechanical threshing operations, appear less tangible in the eyes of the farmers. Four types of metallic frame dryers were fabricated in the workshops of the Centre national de recherches agronomiques (CNRA) in Bambey, and tested in the Centre to determine their relative efficiencies. The four prototypes differed in the type of covering on the upper surface (glass or sheet metal) and by the presence or absence of a chimney. The chimneys, which were of semiparabolic form, were added to the structure to induce an upward hot airflow. Temperatures at various locations inside the dryer were monitored by thermocouples. Wind direction, airspeed at the dryer inlet, and outside air temperature and humidity were also recorded to determine their effects on the air temperature inside the dryer and on the drying of the product. For each dryer, recordings were made covering periods of at least 4 days, with three to six readings taken per day. The results indicated that the temperature difference between the interior and the exterior of the dryer rarely exceeded 10°C. This occurred because, in reality, there was no solar collector feeding hot air to the dryer, thus the interior temperature of the dryer was not much*

---

[1] Centre national de recherches agronomiques de Bambey, Sénégal.

higher than the ambient. To determine whether there were any significant differences between the four types of dryer, and to assess the influence of wind speed, exterior temperature, and time of day, a multiple linear regression model was developed in which the dryer interior temperature was the dependent variable. This solar dryer study will have to be reconsidered, because a temperature increase of only 10 °C is certainly too small given the intense periods of sunshine experienced in Senegal. The solar performance of the dryer is minimal, so that its drying efficiency is not much better than that of a crib-dryer. For this reason, adding a chimney has little effect, although a chimney should induce a hot airflow and lead to better drying if the solar dryer is well designed. Covered plate collectors are more efficient than bare plate collectors.

Scope of Research

The main edible and cash crops of Senegal are millet, sorghum, maize, rice, haricot beans, groundnuts (peanuts), and cotton. Market gardening is of some importance in the Niayes region and on the outskirts of major centres. All these agricultural activities include fairly extensive drying operations before storage to ensure that the products will be preserved well.

The edible and cash crops are generally harvested between mid-September and the beginning of November. Drying of these products starts, therefore, in October and ends in January. During this period, the mean temperature varies between 25.4 and 28.3°C according to climatic zone (coastal, subtropical, Sudanese, or Sahelo-Sudanese), relative humidity varies between 72 and 51%, and vapour pressure between 16.7 and 13.6 mm of mercury (Anonymous 1974, 1978).

A portion of the grain crop is lost before consumption. Losses in the postharvest production chain are due to inadequate methods of drying, handling, storage, and processing. These losses start in the drying stage, which is the first operation in postharvest production. In Senegal, most of the grain crop is dried in the field, apart from a small portion that is intended for immediate consumption. In some cases, entire plants are cut at harvest time and sun-dried directly on the ground. In other cases, the ears are cut and piled in bulk or tied in sheaves of about 10 kg which are left to dry in large heaps on the ground. Under these conditions, during the 7-8 weeks of drying, the grain is attacked and contaminated by rodents, insects, mould, and birds. Improvements in the sun-drying techniques would allow maximum utilization of solar radiation and other climatological factors, a reduction in the various forms of contamination and pollution and hence an improvement in the quality of produce, and a reduction in the drying time for agricultural products. Thus, crop losses due to sudden rainfall, insects, birds, and rodents would be reduced (Fournier 1980).

The aim of this research was, therefore, to test new dryer prototypes that could improve local grain drying, especially for sorghum. Tests were conducted on a natural convection crib-dryer and four prototype dryers equipped with solar collectors. The tests were conducted during 1977 and 1978.

Materials and Methods

Crib-Dryer

The crib-dryer (Fig. 1) consisted of a wooden structure in the form of a parallelepiped 5 x 2 x 2 m, i.e., a loading capacity of 20 m^3. It was raised 30 cm above the ground to ensure good air circulation and to prevent access by rodents and other small animals. The base and the sides of the crib were covered with a metallic screen. Palmyra wood was used as the construction material because it was available and is resistant to termites.

The grain used was sorghum. The ears were tied in sheaves of about 30 kg each and symmetrically placed in staggered rows along the longitudinal axis of the dryer.

Ten dryers of this type were installed in the village of Ndiamsil in the district of Lambaye (Department of Bambey) in 1977 and 1978. It was originally intended to conduct a study on actual product drying including the economic aspects, but this study was subsequently restricted to a cost-benefit analysis.

Solar Dryers

Four prototypes of metallic frame dryers were fabricated and tested at the Centre national de recherches agronomiques (CNRA) in Bambey to determine their relative effectiveness (Figs 2-4). These structures were 3 x 1 x 1 m and were covered at each end by a double mesh, one fine and the other coarse, to prevent access by rodents. The floor and sidewalls of each dryer were covered with black-painted metallic sheet. The four prototypes differed in the type of covering on their upper surface (glass or sheet metal) and in the presence or absence of a chimney: without chimney but with a sheet-metal upper surface (NC/SM); without chimney but with a glass upper surface (NC/G); with chimney and a sheet-metal upper surface (C/SM); with chimney and a glass upper surface (C/G).

The chimneys, which were of semiparabolic form, were added to the structure to induce an upward hot airflow. Also, the dryers having chimneys were equipped with a conical inlet section to provide better directed airflow from the outside into the dryer.

Temperatures inside the dryer were monitored to determine its effectiveness. Wind direction, air speed at the dryer inlet, and ambient air temperature were also recorded to determine their effects on the air temperature inside the dryer and the drying of the product.

Temperatures inside the dryer were measured with thermocouples installed at several locations: at 25, 50, and and 75 cm above the floor. This pattern was repeated every 25 or 50 cm along the dryer. Air speed was measured with a Florite anemometer and wind direction was obtained from a weather vane installed 2 m above the ground. Ambient air temperatures (wet and dry bulb) were measured in the shade with standard thermometers.

For each dryer, recordings were made for periods of at least 4 days with three to six readings taken per day. Each dryer was loaded with 200 sheaves of grain, each weighing 7 kg. The experiment

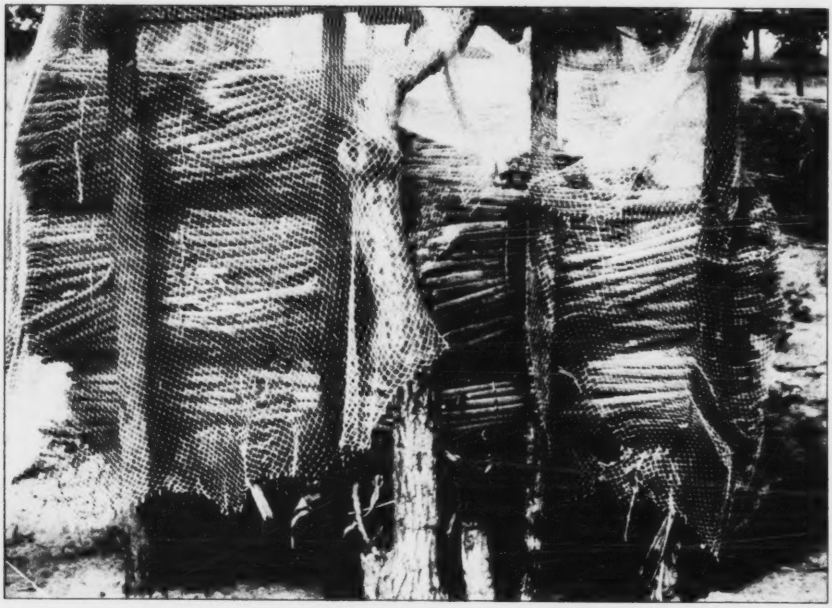


Fig. 1. Improved traditional structure.

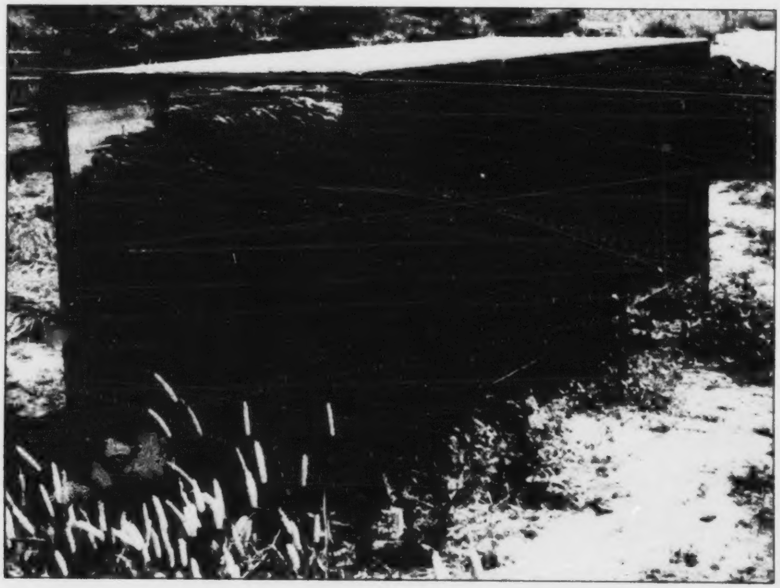


Fig. 2. Dryer with glass upper surface but without chimney.

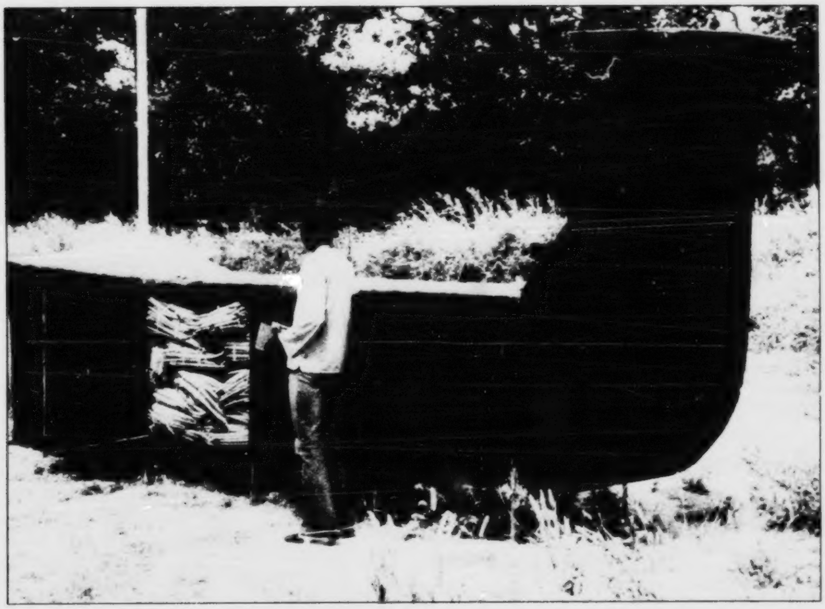


Fig. 3. Solar dryer with glass upper surface and chimney.

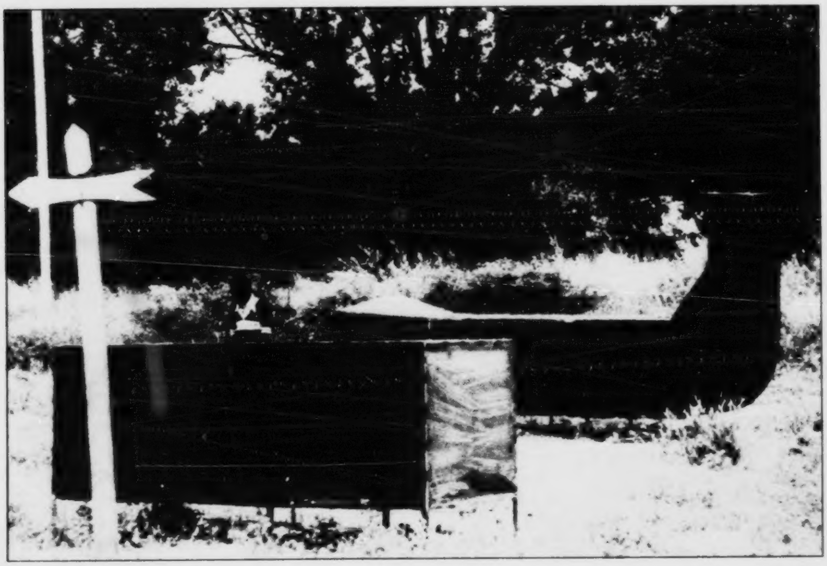


Fig. 4. Two dryers without glass upper surface: one with a chimney, one without.

was devised so as to allow the moisture content of the grain to be monitored, as well as to determine whether air could flow easily through the mass of grain.

Results and Discussion

Crib Drying

Observations on the 10 cribs installed in a rural environment and at the Centre showed that the drying time was between 5 and 6 weeks, or 2 weeks less than the traditional drying time. Nevertheless, the drying time is still relatively long compared with that of other drying methods, conventional or solar.

The main advantage of crib drying is that both drying and storage are much more efficient than with traditional methods. Raising the dryer above the ground ensures better ventilation and hence more rapid drying. It also prevents rodents and most insects from reaching the crop. In crib drying, the surface exposed to insects, birds, and other animals is significantly reduced and, at the same time, airflow through the product is increased. If the frequency of attack by these predators is proportional to the exposed surface area (which remains to be proved), we would expect postharvest losses to be reduced if larger masses of crop are dried on smaller surfaces.

The useful life of such a dryer is estimated to be 10 years. Based on this estimate, economic analysis shows a cost recovery from drying/storage of 1 kg of millet grain of 8-10 XOF[1], which represents 11.5-14.3% of the official sale price of millet (70 XOF/kg). To warrant the construction of such a dryer purely on economic grounds, it must be able to reduce losses directly by 11.5-14.5%. The secondary advantages, for example, rapid release of parcels of land and better distribution of harvesting for mechanical threshing, are less tangible in the eyes of the user (Diop 1979).

Solar Drying

Values for air speed and the exterior (ambient) and interior temperatures at various times of the day for each of the four dryers are given in Tables 1-4. The observations were made over 4-6 days. If the dryer is efficient, this period should be adequate for reducing the moisture content of the grain to a sufficiently low level to ensure good preservation.

The temperature difference between the exterior and interior of the dryer rarely exceeded 10°C (Tables 1-4). This difference is quite small compared with temperature gradients of 30°C or more that have been obtained with some types of dryers under climatic conditions that are much less favourable that those in Senegal (Diop 1979). This occurred because there is, actually, no solar collector feeding hot air properly to the dryer; thus the interior temperature of the dryer is not much higher than the ambient. Moreover, when the dryer is

---

[1] In 1986, 220 XOF (franc de la Communauté financière africaine) = 1.00 CAD (Canadian dollar).

Table 1. Dryer without chimney but with glass upper surface.

Time	Air speed (mm/sec)	Temperature (°C)		
		Exterior	Interior	Difference
20 June 1978				
0840	202.14	22.00	29.38	7.38
0950	200.57	28.00	35.83	7.83
1040	201.43	33.00	38.57	5.57
21 June 1978				
1000	212.38	32.00	38.52	6.52
1155	229.19	35.00	40.52	5.52
1600	230.10	39.00	47.00	8.00
1700	223.43	38.00	42.05	6.05
1740	218.62	31.00	38.79	8.79
22 June 1978				
0845	220.43	27.00	31.31	4.31
0945	221.19	28.00	36.43	8.43
1145	220.38	33.00	38.81	5.81
1200	205.86	34.00	42.14	8.14
1630	242.33	38.00	38.98	0.98
1720	224.57	39.00	38.98	0.02
23 June 1978				
0830	205.95	27.00	28.48	1.48
0930	228.48	27.00	32.76	5.76
1030	238.76	28.00	38.57	10.57
1130	241.62	32.00	40.31	8.31
1310	205.43	34.00	42.93	8.93
1340	223.19	37.00	43.50	6.50

completely filled with ears of grain, the plate that acts as an absorbing surface is totally covered by the product to be dried and is, therefore, useless.

To determine whether there were any signifiant differences between the four types of dryer, a multiple linear regression model was developed. The model is based on the following assumptions: that the interior temperature of the dryer (dependent variable) depends on a number of factors including the time of day, the air speed, the ambient temperature, and whether the dryer is equipped with a chimney or glass upper surface or both. The multiple linear regression model not only provides a means of validating these assumptions, and possibly quantifying the importance of each factor (independent variable) in the expression for interior temperature (dependent variable), but also of comparing the various types of dryer. The model can be expressed in mathematical form as:

Table 2. Dryer without chimney but with sheet metal upper surface.

Time	Air speed (mm/sec)	Temperature (°C)		
		Exterior	**Interior**	**Difference**
20 June 1978				
0826	203.81	22.00	30.50	8.50
0830	200.48	27.00	36.76	9.76
1030	191.43	28.00	38.71	10.71
1735	200.14	28.00	38.90	10.00
1755	200.00	28.00	38.33	10.33
21 June 1978				
0820	200.43	27.00	29.05	2.05
0900	203.52	27.00	33.62	6.62
1000	240.00	33.00	38.62	5.62
1530	237.48	41.00	42.83	1.83
1630	231.71	39.00	43.48	4.48
1730	218.38	37.00	39.07	2.07
22 June 1978				
0800	214.76	26.00	27.10	1.10
0900	217.95	28.00	30.48	2.48
1000	221.86	29.00	36.21	7.21
1110	205.86	33.00	38.86	5.86
1210	213.00	34.00	40.38	6.38
1555	237.38	39.00	43.00	4.00
23 June 1978				
0805	217.52	21.00	27.93	6.93
0905	209.19	23.00	29.19	6.19
1005	233.25	28.00	33.64	5.64
1105	259.76	32.00	36.24	4.24
1205	208.43	33.00	37.90	4.90
1230	201.62	33.00	39.07	6.07

$$Y = B_0 + B_1(x_1) + B_2(x_2) + B_3(x_3) + B_4(x_4) + B_5(x_5) + e$$

where

Y = interior temperature
x_1 = time of day (from 0800 to 1800 hours)
x_2 = air speed
x_3 = ambient temperature
x_4 = presence of chimney on dryer (1, with chimney; 0, without)
x_5 = use of glass upper surface (1, with glass; 0, without)
e = error constant.

Table 3. Dryer without chimney but with sheet metal upper surface.

Time	**Air speed (mm/sec)**	**Temperature (°C)**		
		Exterior	**Interior**	**Difference**
27 June 1978				
1150	203.33	28.00	32.21	4.21
1615	201.29	34.00	41.00	7.00
1725	206.33	34.00	38.36	4.36
28 June 1978				
0830	258.81	27.00	29.29	2.29
0840	238.30	27.00	30.55	3.55
0930	316.48	28.00	33.45	5.45
0940	298.50	28.00	35.35	7.35
1030	333.24	33.00	37.43	4.43
1040	319.70	33.00	38.15	5.15
1130	332.81	33.00	39.52	6.52
1140	333.70	33.00	41.30	8.30
29 June 1978				
0956	218.00	28.00	32.00	4.00
1147	266.00	32.00	38.45	6.45
1623	234.00	33.00	37.00	4.00
1715	250.00	26.00	34.25	8.25
30 June 1978				
0858	237.14	27.00	29.98	2.98
1032	224.76	31.00	37.69	6.69
1155	268.57	33.00	40.50	7.50
1245	272.86	37.00	44.93	7.93
1507	299.05	37.00	44.95	7.95

Neither of the coefficients B_4 and B_5 is significantly different from 0 ($\underline{P} = 0.95$, Table 5). In other words, the presence or absence of a chimney or of a glass upper surface has no significant influence on the dryer interior temperature.

However, time of day (x_1), airspeed (x_2), and ambient temperature (x_3) contribute significantly ($\underline{P} = 0.95$) to the variations in interior temperature (Y). It should also be noted that time of day and exterior temperature are strongly correlated ($\underline{r}^2 = 0.70$). Of all the independent variables, the ambient temperature seems to have the greatest influence on interior temperature (Diop 1979). In future studies, the influence of solar radiation intensity (solar power on the dryer interior temperature) should also be investigated.

Table 4. Dryer without chimney but with glass upper surface.

Time	Air speed (mm/sec)	Temperature (°C)		
		Exterior	Interior	Difference
19 June 1978				
0810	200.00	26.00	28.71	2.71
0925	200.00	28.00	32.55	4.55
1035	254.76	29.00	36.21	7.21
1140	266.67	32.00	39.71	7.71
1253	250.95	32.00	38.10	6.10
1408	220.95	32.00	40.14	8.14
27 June 1978				
1110	206.43	27.00	35.07	8.07
1540	200.00	37.00	41.07	4.07
1710	203.95	34.00	37.88	3.88
28 June 1978				
0805	220.95	23.00	28.21	5.21
0905	207.05	27.00	33.38	4.38
1005	222.29	29.00	36.31	7.31
1105	346.62	29.00	39.64	10.64
1505	258.81	35.00	42.55	7.55
29 June 1978				
0835	205.71	29.00	29.40	0.40
1040	231.43	29.00	36.74	7.74
1515	301.90	33.00	38.48	5.48
1650	262.38	33.00	35.60	2.60
30 June 1978				
0830	214.29	26.00	29.83	3.83
1000	244.76	28.00	35.33	7.33
1130	265.71	33.00	39.83	6.83
1245	255.24	34.00	45.17	11.17
1420	260.48	37.00	47.33	10.33

Conclusions

The crib-dryer is of particular interest because it affords a more effective way of drying and storage than the traditional methods used by the farmers.

The performance of the solar dryers investigated at CNRA in Bambey was very low, particularly in view of the intense periods of sunshine experienced in Senegal. This is mainly due to the poor design of the dryer itself. Because the dryer lacked a high performance solar collector, its efficiency was almost as low as that of the

Table 5. Analysis of variance for linear regression of interior against five variables.

	Degrees of freedom	Sum of squares	Sum of χ^2
Regression	5	1551.79	310.36
Error	80	467.18	5.84
Total	85	2018.97	
		R = 0.77	F = 53.15*

Coefficient	Corresponding variable	Standard deviation	Value of t[a]
B_0 = 4.863	--	--	--
B_1 = 0.299	time of day	0.1245	2.4*
B_2 = 0.0217	wind speed	0.00825	2.63*
B_3 = 0.7575	exterior temperature	0.0894	8.48*
B_4 = -0.854	use of chimney	0.613	-1.39 NS
B_5 = 0.904	use of glass	0.537	1.68 NS

[a] * = significant at P = 0.95; NS = not significant.

crib-dryer. The dryer design was actually that of a "drying box" in which the product itself acts as the absorber (Fournier 1980). For this reason, it is of little significance whether the dryer has a chimney or a glass upper cover. If the dryer were well designed, a chimney could increase the flow of hot air through the dryer and hence improve its drying characteristics. On the other hand, the efficiency of covered plate colletors is higher than that of bare plate collectors only up to a flow rate of 300 m^3/hr. Above that rate, the temperature of the absorber is so low that the radiative losses are small whereas the losses from the cover assume relatively greater importance. The efficiency of the bare collector is then higher than that of the covered collector (Fournier 1980).

The study on these particular solar dryers should, therefore, be generally reworked, with emphasis placed on the design of a high performance collector. Only in this way can the advantage of Senegal's high solar energy be usefully exploited.

Prospects

Agricultural development in Senegal will require more widespread use of crop dryers even though, at present, these dryers are not justified for most of the cereals that are found mainly in the north and north-central regions.

Because solar energy is so readily available, research should focus on the design of solar dryers. "Compared with natural drying, even the most rudimentary solar techniques can reduce average drying times by 50%. Aside from quantitative benefits, the quality of the product is almost always improved. The high temperature inside the dryer eliminates the risk of infestation. Equally, the initial protein content is virtually all recovered" (Fournier 1980).

Research on dryers should, therefore, be continued to perfect a high performance hot air generator that can be fabricated from locally available materials: sheet metal, corrugated metal sheet, plastic film, etc. The performance of the dryer should be measured against the following parameters: temperature gradient between the exterior and interior, drying curve of the product, drying time of the product, germinal power of seed, nutritional and organoleptic quality of the product, useful life of the dryer, and the cost of drying.

From an economic standpoint, the criterion of profitability dictates the most widespread possible use of the dryer. The range of drying products should, therefore, be diversified to spread over the whole year (Fournier 1980).

At all events, preliminary studies should clearly demonstrate the economic viability of such techniques and their superiority over methods now in use. Because drying is essentially the first stage in postharvest production, it is clear that changes at this stage should be accompanied by corresponding changes at the later stages of threshing, storage, and processing if the efficiency of the overall postharvest production chain is to realize its full potential.

Future Research on Solar Drying

As was mentioned earlier, the use of solar dryers for drying cereals in central and north-central Senegal is not economically justifiable. Current price levels and the disorganization of the cereal production network do not warrant any additional investment by the producers. They would adopt such an approach only if prices were higher and there were an outlet for surplus production.

This is not intended to imply that all research on solar dryers should stop. The producers in the south and south-east of the country are faced with real drying problems for their crops (rice, maize, sorghum, and sanio). With the coming of the Diama dam, the double culture system that is envisaged will necessitate the use of dryers by producers. Finally, some foodstuffs such as fish and vegetables require adequate drying for good preservation. Research on drying techniques for these products is clearly justified, but it should be predicated on the real needs and technoeconomic capacities of the potential users.

References

Anonymous. 1974. Sénégal 1960-1973: 14 ans de développement économique et social. Marchés Tropicaux, 1493, 21/06/74 (special issue).

———— 1978. L'industrie sénégalaise: l'environnement socio-économique. L'agriculture, élément essentiel de l'économie nationale. Marchés Tropicaux, 1684, 17/02/78.

Diop, A. 1979. Projet 3-P-760026 Technologie post-récolte: Résultats techniques. Centre national de recherches agronomiques, Bambey, Sénégal.

Fournier, M. 1980. Théorie du séchage. Intérêt et pratique des capteurs plans. Technologie des séchoirs agricoles solaires. Intérêt des solutions polyvalentes. In Conservation des denrées alimentaires cultivées en climat chaud et humide. Proceedings of the First International Symposium on Technology held at Yaoundé, Cameroon, 5-10 November 1979. L'Association des universités partiellement ou entièrement de langue française, Montreal, Canada.

PROBLEMS AND SOLUTIONS FOR NATURAL-CONVECTION SOLAR CROP DRYING

Michael W. Bassey,[1] Malcolm J.C.C. Whitfield,[2] and Edward Y. Koroma[3]

Abstract *— Solar crop drying is an important postharvest practice in African countries. Traditional practices are known to have several drawbacks that can be eliminated using solar energy as a heat source in improved drying systems. Unfortunately, these solar dryers have not yet made any significant impact in rural areas. This paper discusses the prerequisites for the development of natural-convection solar crop dryers, using experience from research activities in Sierra Leone. Studies critically discussed include: initial needs assessment; climatic conditions and available energy sources; experimental studies on hybrid and solar dryers, pointing out useful contributions made and constraints in their design; activities to consider during field testing; and possible areas for improving research in solar drying. Substantial experimental work done in Sierra Leone on solar dryers provides some insight on their operation. These results on chimney design, drying curves, air heater configurations, airflow improvement, etc. should be supported by analytical work. Although more concerted technical effort is required before solar dryers can be effectively used, it is pointed out that success is dependent on cost and effective field testing, using an interdisciplinary team.*

Introduction

Drying is an important process used in nearly all developing countries to preserve both food and nonfood commodities. Traditional methods of drying, although satisfactory in some cases, suffer from certain drawbacks, particularly exposure of the commodity to rain, dust, birds, and rodents and improper and inadequate drying, which lead to inferior products. For certain foodstuffs, improper drying causes the development of aflatoxin and other toxic moulds that are detrimental to human and animal health.

---

[1] International Development Research Centre, BP 11007, C.D. Annexe, Dakar, Senegal.

[2] Department of Mechanical Engineering, University of Sierra Leone, Freetown, Sierra Leone.

[3] Rice Research Station (Rokupr), P.M.B. 736, Freetown, Sierra Leone.

The need to improve traditional drying and thus to improve product quality and the quantities that can be handled is generally agreed. Because of the various flaws in traditional drying, interest has, in the last decade, been focused on the design and use of improved drying systems, mainly for foodstuffs, using solar energy as a heat source. Although some of the solar dryers show promise for rural applications, they have unfortunately not found widespread use in developing countries for several reasons.

Several studies have been done in Africa to develop solar dryers for commodities such as timber (Okoh 1985), rice (Bassey 1982b), onions (Ba et al. 1982), vegetables (Ali and Sakr 1982), pyrethrum (Sebbowa 1985), maize (Johnston 1984), and fish (N'Jai 1985). Other studies have been concerned with assessing the nutritional values of dried food (Gomez 1982) and improving dryer performance (Bassey 1982a, 1985a; Whitfield 1985a; Othieno 1985).

Despite the contributions made by these researchers and many others, solar dryers are not widely used by farmers in Africa. In our opinion, the reasons for this are sixfold.

- A general lack of preliminary studies before a dryer is built to identify the commodities that must be dried;
- Improper sizing of the dryers to match the farmer's needs, which makes their use uneconomical or inappropriate;
- High capital cost of the dryers due to the low income of most rural farmers;
- Poor performance of the dryers as a result of design flaws;
- Low airflow through the dryers, because air is circulated by natural convection (electricity or other energy forms to increase airflow are not available in most rural areas); and
- Improper or insufficient testing of the developed dryers by the intended users.

Proper planning of research activities in solar drying is, therefore, needed to obtain valid results that will lead to the widespread use of improved drying systems.

Considering the points raised above, we discuss here those approaches that could be adopted by workers involved in solar drying research and development for application in Africa. To make the presentation practical and relevant to Africa, we use examples of research work carried out in Sierra Leone over several years. Only natural-convection solar drying is discussed here.

Initially, we review those studies that should be carried out before a dryer is designed, i.e., what crops are to be dried and how much energy is available to dry them. The design, development, and operation of solar drying systems and the related problems are also discussed. Finally, we suggest areas for further research activities and the strategies that should be used to obtain useful results.

Drying Requirements

Problem Identification

In practice, the first step in developing improved solar drying is to identify the specific problem. Taking into account the scarcity of funds, both from national and external sources, the problem should usually be of national importance and its solution should be economically viable.

To correctly identify a drying problem, the people experiencing it must first be contacted. Studies on solar drying were initiated in Sierra Leone as a result of the involvement of one of the authors in a country-wide rural-technology survey to identify traditional technologies that needed improvement. Contacts with various farmers indicated that, although traditional drying yielded satisfactory results, useful changes could be made. Although it was then difficult to determine precisely what commodities would benefit from improved drying, those initial contacts with farmers did show their concern and wish to improve the drying of their crops.

Assessment of Needs

Many solar-drying projects have been based on only superficial identification of a drying problem. Such an approach is unsatisfactory and could easily lead to a solution that is useless to the intended beneficiary.

Having established that certain crops might benefit from improved drying, a survey was carried out throughout Sierra Leone to obtain more detailed information on target crops and on the farmers' views and experience. Based on knowledge of areas of agricultural activities and within the limits of public transportation and human resources, the survey areas were chosen as shown in Fig. 1. The questionnaire used was designed by one of the authors (a mechanical engineer) with no social scientist's input. The enumerators were 3rd-year mechanical engineering students who could speak the languages of the various areas visited. They were well briefed concerning all aspects of the survey. Farmers participating in the survey were randomly chosen and the enumerators were supervised in the field by one of the authors and a research assistant.

Although the method adopted for the survey gave satisfactory results, certain aspects could have been better organized: for example, the questionnaire was prepared without the input of a socioeconomist. This is a common practice in projects that develop technologies for use in rural areas: it is also a practice that should change, however, certain constraints limit interdisciplinary collaboration.

Many socioeconomists in Africa are removed from the rural environment and, at the same time, their interest in the development of technology has until recently been limited. Engineers or physicists, on the other hand, either are unwilling to solicit the participation of socioeconomists or do not know how to interact with them. In the case of this survey, the constraints of time and lack of transport made it difficult to interact with agricultural economists and other

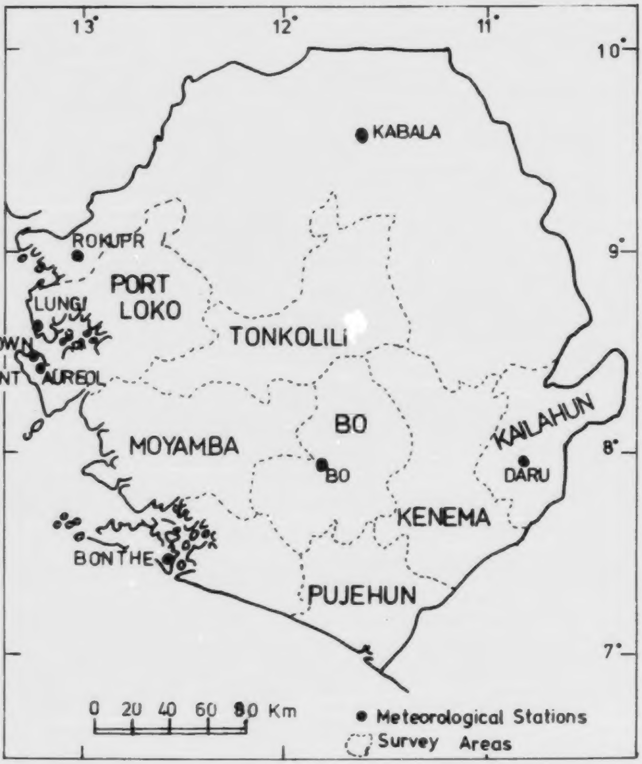

13°
12°
11°
10°
9°
8°
7°
KABALA
ROKUPR
PORT LOKO
LUNGI
FREETOWN
MOUNT AUREOL
TONKOLILI
BO
BO
KAILAHUN
DARU
MOYAMBA
KENEMA
BONTHE
PUJEHUN
0 20 40 60 80 Km
● Meteorological Stations
Survey Areas

Fig. 1 Areas where survey on traditional drying was carried out and locations where meteorological data were obtained, Sierra Leone.

nontechnologists who could have had valuable input during the preparation of the questionnaire and the field work.

Because the enumerators were chosen from their home districts, it was relatively easy to obtain reliable information from the farmers. In addition, the familiarity of the enumerators with the needs of both the farmers and the survey made a very important contribution to the success of the survey.

Typical Results of Survey

The questionnaire used was simple to implement. About 700 copies were filled for various crops and the data have been analyzed and reported (Bassey 1982b). Typical results are briefly discussed below.

Three methods of drying the crops were identified during the survey: in the open air, over a fire, or in-storage in traditional silos. Open-air drying was the most important method used although about 20% of farmers used fire: the actual value depended on the specific crop. Although most of the farmers were generally happy with the traditional methods of drying they were using, they wished to have a better quality product for most crops. They wanted to reduce drying times and losses when handling rice, the crop cultivated most frequently by farmers (Fig. 2).

Other results obtained from the survey were: the percentage of farmers (for the total for each crop) cultivating various land areas; the quantities of the various crops being dried by the farmers; losses for each crop as perceived by the farmers; the duration of drying for each crop; the amount farmers were willing to pay for improved drying systems for various crops; and the percentage of farmers who cultivate the various crops for sale or household consumption. Such results provide a starting point for the development of solar dryers. In Sierra Leone, most crops surveyed are harvested during the dry season, i.e., October to May (Fig. 3). Based on the survey data, the needed capacities of the dryers can be determined to allow for the economic

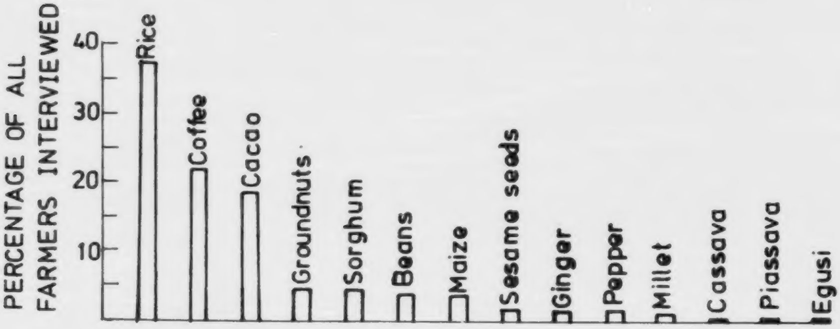


Fig. 2. Percentage of farmers interviewed who cultivate a given crop.

Crops	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Rice			---	---	---	---	---	---	---			
Cacao		---	---	---	---	---	---	---	---	---	---	---
Coffee						---	---	---	---			
Groundnuts	---	---	---	---								
Millet				---	---	---						
Pepper	---	---	---	---								
Ginger							---	---				
Maize		---	---									
Sorghum						---	---					
Sesame seed						---	---					

Fig. 3. Period of harvest for various crops in Sierra Leone.

viability of a given drying system. In addition, results of such a survey indicate the possibility of using a dryer for more than one crop to maximize its use.

Although the usefulness of a needs assessment survey is unquestionable, the results may prove to be quite frustrating if the questionnaire has not been adequately designed. Too many or too few questions may be asked during the interviews. For example, a lengthy questionnaire may result in great effort being necessary during data reduction especially if a computer is unavailable, as in the case reported by Bassey (1982b). Where possible, someone experienced in analysis of survey data should be involved in the design of the questionnaire and interpretation of results.

The improper sizing of solar dryers and high capital costs, mentioned earlier as two of the reasons for the lack of the application of these technologies, can be partly resolved through an initial survey of the farmer's needs and views. This approach has not been routinely adopted by researchers, as mentioned earlier, partly because it is a time-consuming and frustrating exercise and needs reliable staff as well as transport facilities.

For Sierra Leone, the results indicate that rice, cacao, and coffee are three of the main crops (Fig. 2) that can benefit from improved drying. In view of the national importance of rice, work has been focused on developing improved drying systems for this grain. Cacao and coffee are primarily export crops.

Drying Characteristics and Quality

The interdisciplinary nature of solar drying is often underestimated. Once a crop has been identified for solar drying studies, certain information must be obtained before an appropriate solar-drying system can be developed. Some of the basic information is:

- Moisture content of the crop before drying starts;
- Equilibrium moisture content of the crop at the storage temperature;
- Maximum allowable temperature of the air and duration of continuous exposure to this temperature;
- Influence of the rate of drying, exposure to solar energy, and air temperature on the nutritional and organoleptic quality of the crop; and
- Pretreatment necessary for the crop.

Information on these aspects of the research must often be obtained with the help of food scientists, microbiologists, etc. Although published data on many crops often exist, particularly on the moisture content of harvested crops, and can reduce the work that must be done, little work has been done on drying characteristics and quality of crops in Sierra Leone. In the case of rice, which has been of interest for some time, more information is available in the literature. Experience indicates that it is of the utmost importance, first of all, to understand the drying characteristics of the crop and then design the dryer to process the crop under the optimum drying conditions. Failure to do this may result in a product that is inferior to that produced with traditional drying.

Climatic Conditions and Available Energy

Knowledge of the climatic conditions and availability of solar energy is a prerequisite in solar drying. However, reliable meteorological data in many countries in Africa are often difficult to find because of lack of equipment, poor maintenance, and unreliable staff. Sierra Leone is no exception and, although several meteorological stations do exist, their state is far from being satisfactory. They are not well maintained and certain important equipment is unavailable. Furthermore, the available records of climatic data are not in a form that can be used readily.

Climatic Data

A study has been carried out to organize certain meteorological data available from several stations throughout the country. This involved visits to eight meteorological stations (Fig. 1), where data were obtained for 1970-1980. From the data, monthly mean daily values for maximum and minimum temperatures, relative humidities, number of rainy days, and sunshine duration were deduced and have been fully reported (Bassey 1982b).

The variation of the various climatic parameters shows that the operation of solar dryers within the country is location specific. Inland areas tend to have higher sunshine duration, higher solar radiation, and lower relative humidities compared with coastal areas. Sunshine duration is about 6-9 hours during November-April, the dry season, compared with 2-4 hours during May-October, the rainy season. Relative humidities are about 80% throughout the year.

Solar Radiation

There is effectively no information on solar radiation apart from that reported by Bassey et al. (1978) and Bassey (1982b). The former study attempted to use measured solar radiation obtained with Gunn-Bellani equipment in a single location to determine an appropriate formula for predicting total solar radiation for the country. However, because the solar-measuring equipment had not been maintained, the measured total solar radiation values were grossly in error and gave values for desert areas! The second study used climatic data for 11 years and limited data on measured total solar radiation to predict solar radiation for specific locations throughout the country (Fig. 4).

Although these results allow useful work to be carried out on solar dryer design, reliably measured solar radiation data for at least 5 years are still needed. This can, however, only be achieved with equipment that is powered by batteries, because the electricity supply in the country is unreliable. The locations and numbers of such equipment need to be carefully determined so that useful isoradiation maps can be developed.

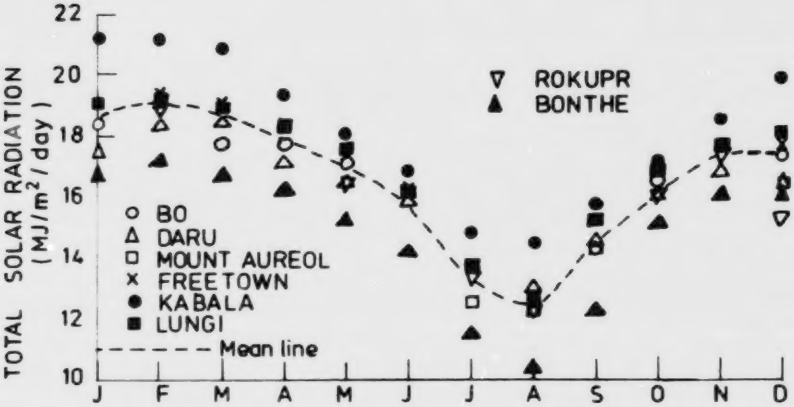


Fig. 4. Estimated monthly mean daily total solar radiation for various locations in Sierra Leone. Note: values for Mount Aureol frequently coincide with those for Lungi.

Auxiliary Heat Sources

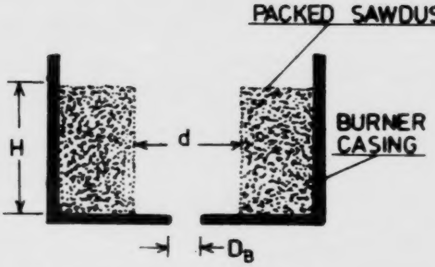
Based on the survey and on climatic data for Sierra Leone, it appears that solar energy alone may be insufficient for drying certain crops effectively during certain periods. Efforts have, therefore, been made to investigate a simple method of burning waste material such as sawdust in a burner (Bassey 1983a). The method of burning the sawdust consists of making a vertical hole through the packed material, lighting and allowing the material inside the hole to burn (Fig. 5). Results reported by Bassey (1983a) consisted of mathematically characterizing the burning process and developing equations that could be used to design burners for various applications. This burner has been used to produce heat to operate various types of equipment, including a hybrid crop dryer (Bassey 1983b, 1985b).

Solar energy, being intermittent in nature, cannot satisfy all drying needs. However, few attempts in African countries have been made to investigate auxiliary systems to aid solar drying. The use of a supplementary source of heat cannot be economical in many cases, e.g., for very small-scale applications, because of the initial capital investment needed, but for larger drying systems the volume of the crop may justify such a system.

Equipment Design and Development

Design Information and Constraints

Most solar dryers are designed without considering the commodity to be dried. In many cases, a dryer is built first and then tested to determine how well it dried various crops. Furthermore, dryers are built with little consideration of such meteorological conditions as ambient relative humidities, air temperatures, and solar energy



D_B = air inlet diameter
d = burner hole diameter
H = packed height of sawdust

Fig. 5. Schematic of the hole-through-sawdust burner.

availability. Thus, solar drying could be considered as "a technology looking for a problem" rather than "a technology developed to solve a problem." This approach must be changed.

The information needed to design a solar drying system must be obtained at the farm level, from meteorological stations, and from the literature. Problems in design arise from the need to keep the cost of the dryers low to match the low income of the potential users because imported materials needed in the design are expensive. A further design constraint is that electricity is expensive and generally unavailable in most rural areas so that most dryers cannot use fans for circulating the heated air. Even with these constraints, useful solar crop dryers can be designed (Bassey 1982c).

Solar hot-air collectors and drying chambers in which air is circulated by means of a fan are designed routinely. However, where natural circulation is used, designs have presented problems due to their low airflow rates. Satisfactory design procedures for indirect natural-flow dryers are lacking because the fluid-flow and heat-transfer processes involved during operation of these dryers, as a means of matching airflow rates and air temperatures through the crops, have not been actively investigated by researchers.

Work on solar dryer design in Sierra Leone has concentrated on using supplementary heat sources, improving airflow rates, utilizing local materials, and understanding the operation of indirect natural-flow solar dryers. These are considered to be areas where significant progress can be made.

Hybrid Dryer

Various aspects of the design and operation of the hybrid dryer have been reported (Bassey 1985b) but are discussed briefly here. The dryer has two main elements, the actual drying cabinet and a sawdust burner to produce supplementary heat (Fig. 6). The dryer consists of a direct solar dryer cabinet designed to operate under load at temperatures up to about 70°C so that a wide range of crops can be dried.

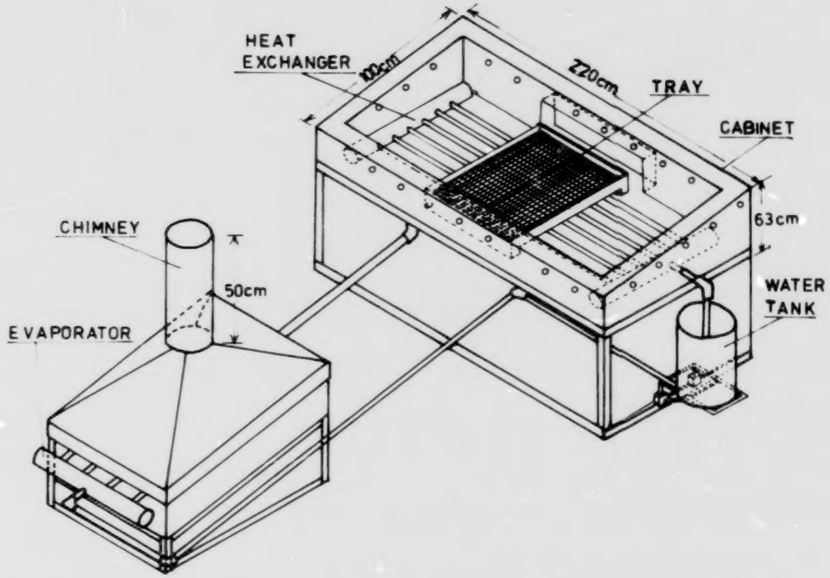


Fig. 6. General view of hybrid solar/sawdust crop dryer.

It was designed using the knowledge of incoming solar radiation, amount of water to be evaporated from typical crops, the design procedure for the sawdust burner (Bassey 1983a), and basic heat-transfer principles. It was assumed in the design that the energy input by the burner to the drying cabinet was 400 W/m^2, burner efficiency to convert water to steam was 10%, condenser efficiency was 50%, and a load of sawdust would burn for 4 hours.

The drying cabinet is constructed of plywood (1.25 cm thick) with double walls that are separated by a 10-cm thick layer of wood-shaving insulation. Holes (2.5 cm diameter) were drilled in the bottom of the cabinet and near the top of the vertical walls to allow air to enter and leave the dryer. Crops to be dried were placed on three trays that could be inserted and withdrawn through a door at the back of the dryer. The top of the cabinet was covered by a single glass cover (0.16 cm thick) with an area of about 2 m^2.

The burner consisted of 28 burner holes (2.5 cm initial diameter), spaced at 10 cm between centres, and arranged in four rows. Four galvanized iron pipes (110 cm long, 2.5 cm diameter) were mounted directly over the burner holes. Water in these pipes was evaporated and the steam passed through the heat-exchamger pipes in the drying cabinet and then vented to the atmosphere.

Tests were carried out on the dryer under no-load conditions and under load using okra (Hibiscus esculentus L.). Results indicate that the hybrid dryer performs very satisfactorily, giving a range of working temperatures depending on the combination of heat sources used.

Under no-load conditions (Fig. 7), the hybrid dryer reached satisfactory working temperatures using solar energy alone, sawdust

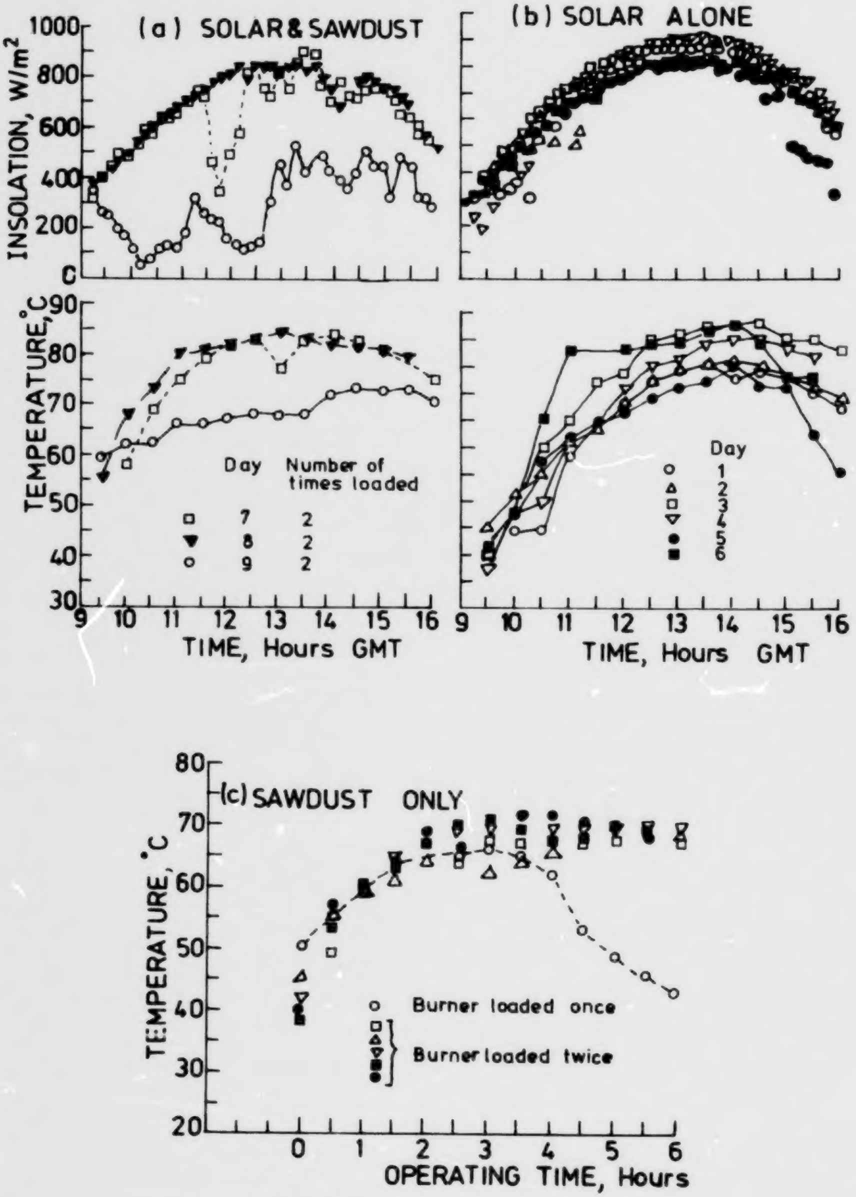


Fig. 7. Variation of temperatures in hybrid dryer cabinet under no-load using various heat sources.

alone, or combined solar energy and sawdust. Thus, on days when the solar availability is good (Fig. 7b), it may not be necessary to use a supplementary heat source. However, when the solar radiation is low, the auxiliary burner must be used to maintain a high enough cabinet temperature (Fig. 7a, day 3). The number of times the burner must be recharged will depend on the incoming solar radiation (for all the tests shown in Fig. 7a, the burner was only loaded twice). Using the burner alone, the dryer can be maintained at a constant temperature only if it is recharged (Fig. 7c).

The okra used for the on-load tests was cut into 1 cm pieces and loaded onto the trays; about 10 kg were dried during each test. Typical results for the three modes of heating are shown in Fig. 8. Temperatures in the cabinet during drying were highly dependent on the available solar radiation when solar energy alone is used (Fig. 8a). However, when the sawdust burner is used as a supplementary heat source, the dryer temperatures can be kept fairly constant by additional loading of the sawdust burner (Fig. 8c).

Although open-air drying can give the same rate of drying as using solar energy alone in the dryer (Fig. 8a, moisture content graph), use of solar energy and sawdust simultaneously (Fig. 8c) halves the drying time. More importantly, however, the burner allows drying to continue when solar energy is not available (simulated in Fig. 8b, moisture content, by the results for open-air indoor drying) and the okra would become mouldy and rot if it were not dried.

The quality of the dried okra was evaluated in terms of its texture, colour, and how easily it could be pounded into flour compared with the open-air-dried product. The dryer gave a greener product that was more crunchy and more easily pounded compared to open-air-dried okra. Also, mould was noticed on the open-air-dried okra whereas the product from the dryer was mould-free.

Although further quality tests should have been carried out and other crops tested on the dryer, this was not possible due to financial and personnel constraints. Efforts should be made to continue work on this dryer, however, to investigate other forms of agricultural waste that could be used in the burner and to improve its overall performance.

Indirect Natural-Convection Dryers

Natural-convection dryers consist of three main components: an air heater, a drying chamber, and a device to induce airflow. Studies in Sierra Leone have been concerned with improving chimney design to increase the flow of heated air through the crop; understanding the interaction between the various parameters influencing the operation of these dryers; and improving the design of the dryers so as to make them more appropriate to local needs. The basic dryer configurations studied are shown in Fig. 9.

Chimney Design and Airflow

Chimneys used on natural-flow solar dryers are simple cylindrical ducts attached to the top of the drying chamber. Although they are intended to increase airflow due to the warmer column of air (with respect to the ambient air outside the chimney), it is suspected that they actually reduce airflow for various reasons.

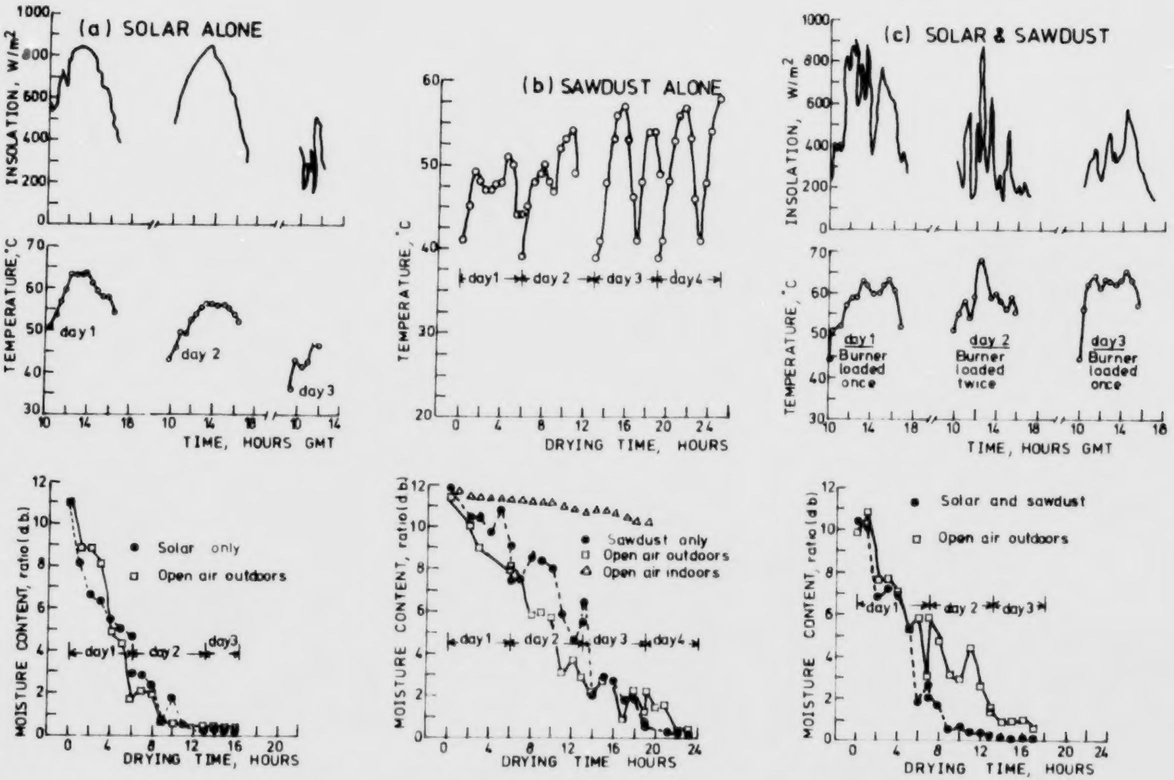


Fig. 8. Variation of temperatures in hybrid dryer cabinet and drying curves for okra for various operating conditions.

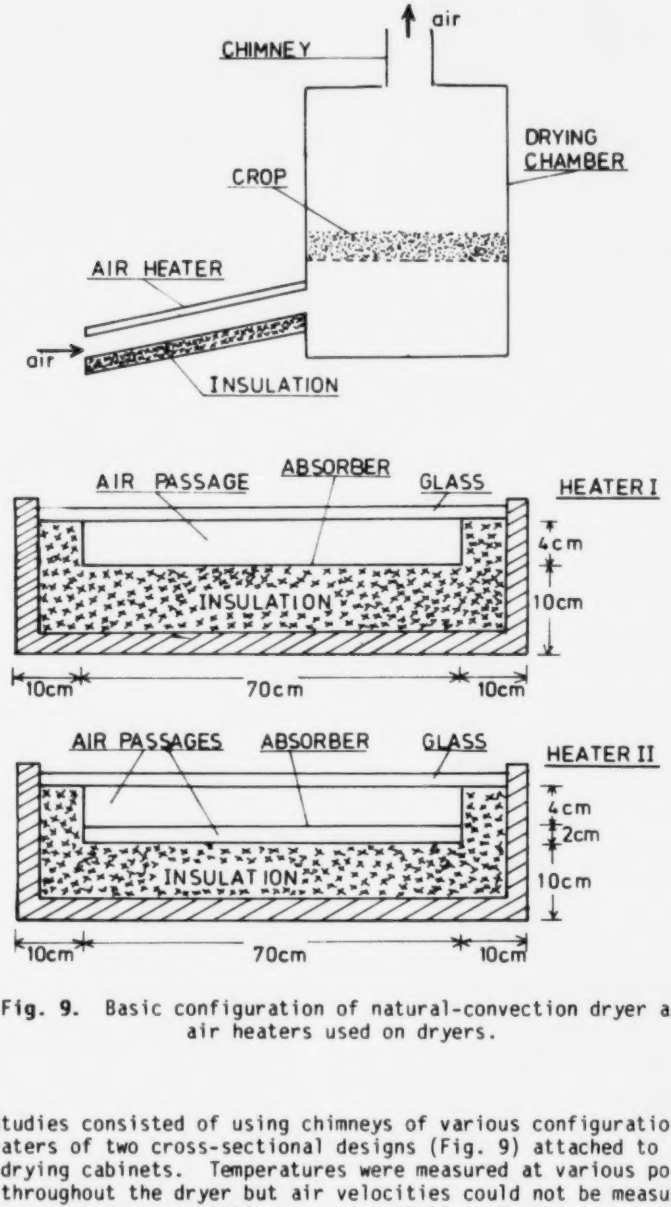

air
CHIMNEY
DRYING CHAMBER
CROP
AIR HEATER
air
INSULATION
AIR PASSAGE
ABSORBER
GLASS
HEATER I
4cm
10cm
INSULATION
10cm
70cm
10cm
AIR PASSAGES
ABSORBER
GLASS
HEATER II
4cm
2cm
10cm
INSULATION
10cm
70cm
10cm

Fig. 9. Basic configuration of natural-convection dryer and air heaters used on dryers.

Studies consisted of using chimneys of various configurations and air heaters of two cross-sectional designs (Fig. 9) attached to identical drying cabinets. Temperatures were measured at various positions throughout the dryer but air velocities could not be measured because proper instrumentation was unavailable. Tests were carried out under no-load and under load using rice.

The chimneys were all made of 0.16-cm galvanized iron sheet and had an internal diameter of 15 cm. The following five types were tested: 38 cm high, unpainted, painted black outside, or painted black outside and surrounded by transparent plastic; and 180 cm high, painted black outside or painted black outside and surrounded by transparent plastic. Where a plastic cover was used, the air gap between the plastic cover and the chimney surface was 2 cm.

Results of this work have been reported and discussed by Bassey (1982a, 1985a). Because no airflows were measured, temperatures in the dryer cabinet were used to indicate the performance of the chimneys. From the data obtained over a 3-year period, mean solar radiation intensities are plotted against mean temperatures in the drying chamber under no-load conditions (Fig. 10).

Although there is considerable scatter due to cloud cover, different chimneys gave different temperatures. For a given height of chimney, the dryer using the air heater with a single air passage (dryer I) gave the highest cabinet temperatures when the chimney was painted black, and then covered with plastic. Taller chimneys on dryer I give lower temperatures. In dryer II, which has two air passages, dryer temperatures decreased progressively with black paint and plastic covering. Increasing the height of the chimney increases the dryer temperatures.

The responses (Fig. 10) have been explained by possible increases and decreases in air mass flow resulting from the heat gained or lost by the chimney (Bassey 1982a, 1985a). Also, the temperatures in the dryer beneath the crop are substantially higher than those in the chimney, due to the moisture removed from the crop by the air. This results in reduced airflow and makes the dryer inefficient.

Therefore, because of the intermittent nature of solar energy and prevailing ambient conditions, tall black chimneys should only be used under clear sky when there is little or no wind and ambient temperatures are high. Shorter chimneys covered with a transparent cover are suggested for cloudy, windy environments to minimize heat loss from the chimney. Such chimneys may also be useful at higher latitudes for heating the air inside them so as to increase the buoyancy force.

Although these results have helped in gaining some insight into the possibilities of improving dryer design, they should not be considered conclusive. Mass flow rates must be measured to support arguments presented.

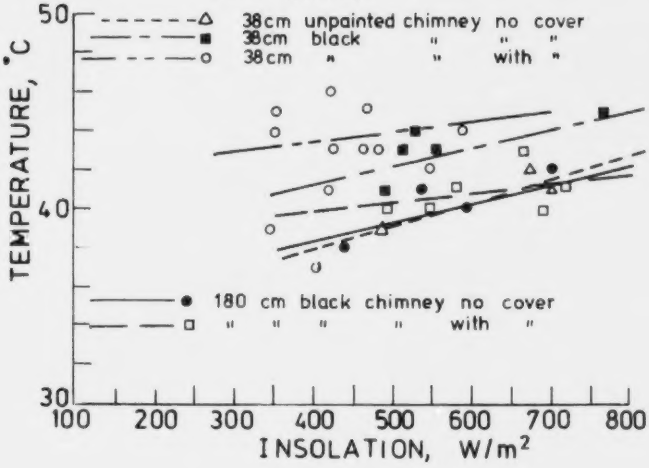
Parameters Affecting Dryer Performance

In addition to work on chimney designs, studies have been done to obtain a better understanding of the performance of indirect solar dryers under various conditions.

Comparisons between the two air heaters shown in Fig. 9 have suggested that a simple heater with a single passage may be adequate for natural-flow dryers (Bassey 1985a). Useful data on the effect of solar radiation on temperatures at various positions in these dryers are also available for further design work. In addition, the relative performance of the dryers investigated in drying various thicknesses of rice beds have been documented (Bassey 1982b).

It should be mentioned that some results for the variation of

(a) DRYER I



(b) DRYER II

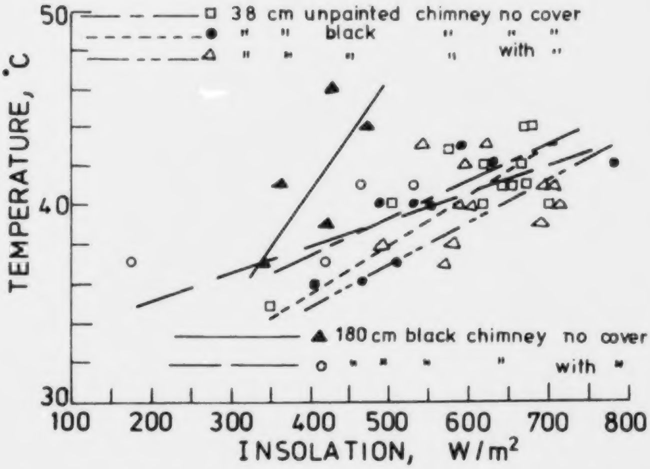


Fig. 10. Variation of daily mean temperatures in the dryers with mean solar radiation intensities under no-load, for various chimney configurations.

moisture content of rice with time show substantial scatter in the data points especially when the rice bed is deep (Fig. 11). This is due to the sampling procedure used. During experiments, the rice bed was thoroughly mixed before each sample, consisting of a few grams,

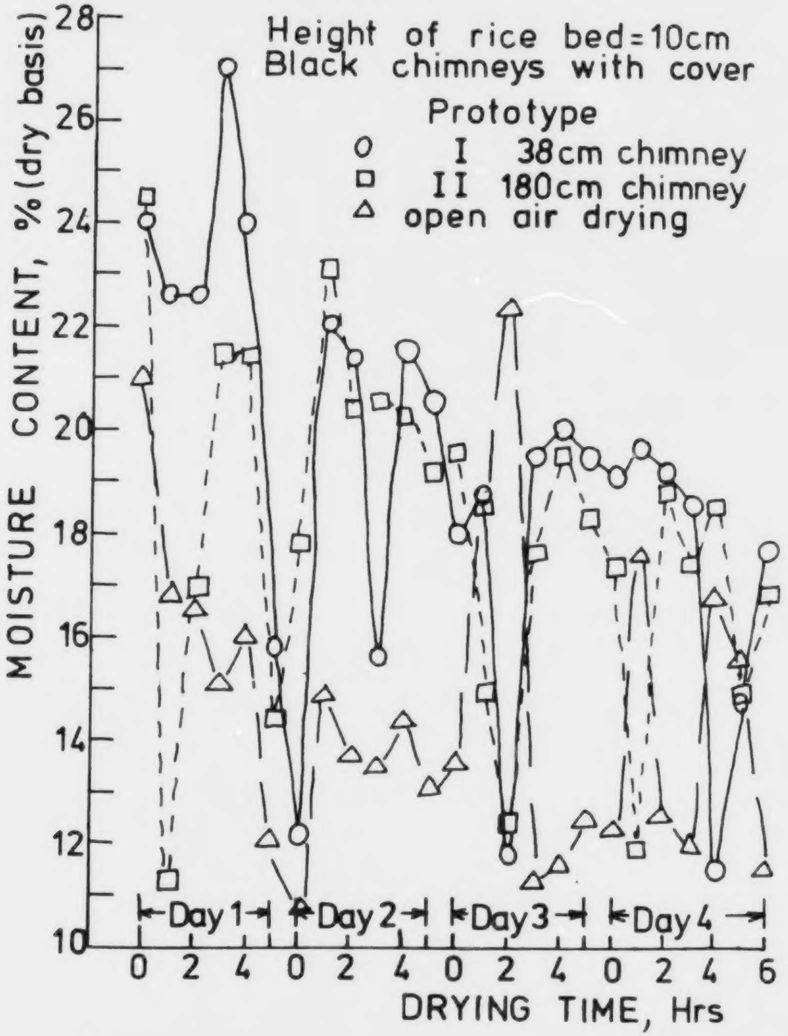


Fig. 11. Variation of moisture content of rice showing the effect of inadequate sampling.

was taken for moisture-content determination (using the oven method). However, some of the samples were probably representative of grain either at the bottom of the rice bed (where the rice was quite dry) or at the top of the bed, where the rice was wetter. Because the samples chosen were very small compared to the bulk of the rice in the dryer, scatter was observed in the data. (This phenomenon has also been observed in various results reported in the literature.)

More reliable moisture-content results could be obtained by weighing the whole bulk of the rice during experiments. However, such a technique would entail relatively sophisticated equipment that was not available when the tests were being conducted.

Despite these apparent inaccuracies in moisture-content data, the results have been satisfactorily used in the development of numerical simulation of the performance of indirect natural-convection dryers (Oosthuizen et al. 1985).

Studies in Sierra Leone indicate that the operation of natural-flow indirect solar crop dryers under conditions of changing cloud cover is very complex. Although cloud cover causes some scatter in the data, it is possible to correlate the mean daily temperatures in the dryer to the mean daily intensity of radiation. Such information allows similar dryers to be compared.

In general, the temperatures of the air underneath the crop are increased compared to the no-load condition. Also, the temperatures above the crop are substantially different from those below it and often close to ambient conditions. These observations suggest that the assumption of a uniform density of air throughout the dryer during design may need to be reconsidered.

Dimensioning of Natural-Convection Dryers

Using experience gained from work where a basic dryer design was specified (Bassey 1982b), further work has been done in Sierra Leone by Whitfield (1985b) to optimize various dimensions of the dryer for optimum flow rates of air. In this case, however, temperatures were measured at various positions in the dryer and air velocities were measured inside the chimney under no-load conditions. The results allowed the effect of heating, cooling, and insulating a chimney to be explained. Detailed measurements of mass flow rates and temperatures under load are, however, needed to substantiate the explanations that were based on no-load tests. However, because of the complex relationships among all governing parameters, it is difficult to be positive about any explanations that are based only on experimental work or to use such studies to optimize the dimensions of dryers.

Insulating the dryer cabinet with a 7-cm thick layer of wood shavings increased the mass flow rate of air only slightly under no-load conditions (Whitfield 1985a). More measurements under load are required to support these observations.

No-load tests were carried out to find the optimum diameter for the chimney using the dryer configuration shown in Fig. 9 with heater 1 (Whitfield 1984a). Mass flow rate increased with larger chimney diameters (Fig. 12). Although these results show that the chimney diameter should be increased, experiments under load would have been more useful. However, the tedious nature of taking such data under the existing conditions (without data-acquisition systems) during the tests was a constraint.

Earlier work (Bassey 1982b) led to the recommendation of an air heater such as that shown in Fig. 9, that has a single air passage 4 cm high. This configuration was derived using simple heat-transfer and fluid-flow formulations and assumptions based on experience with

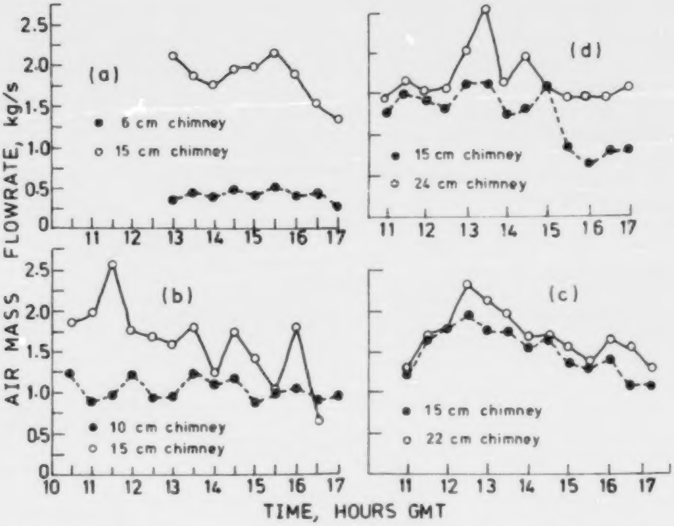


Fig. 12. Dependence of air mass flow on diameter of chimney under no-load, for dryer using single passage air heater.

the operation of natural-convection dryers. Another recommendation for the dimensions of dryers is that the surface area of the transparent cover on the air heater should be equal to the horizontal area of the drying chamber. In addition, it has been recommended (Bassey 1982a, 1985a) that chimneys should be short (less than 40 cm) and insulated to prevent heat loss to the ambient air. Results of other studies (Whitfield 1985b) suggest that the cross-sectional area of the chimney should be more than 16% of the horizontal area of the drying chamber.

In the absence of reliable methods for sizing dryers, these recommendations can be used as guidelines. Better relative dimensions of various parts of natural-flow dryers could be obtained using computer modeling, which minimizes the amount of experimental work needed.

Construction Materials

One of the constraints in obtaining an appropriate dryer is the high cost of materials. Various suggestions have been made concerning the choice of materials (Bassey 1982c), but the rapidly changing economy in a country such as Sierra Leone creates a situation where an appropriate design today may be inappropriate in a few months because the materials are lacking or cost too much.

Experience in solar drying in this country shows that the use of plywood, glass, and galvanized iron as the main construction materials is inappropriate at present because of their high cost. Therefore, the capital cost of dryers has been reduced by making them out of mud or clay bricks. A design now being tested uses these blocks for the sides of the dryer, straw as the insulation in the air heater, galvanized iron as the absorber plate, and glass as the transparent cover. This dryer (Fig. 13) will substantially reduce the capital cost but needs to be tested to determine the influence of its thermal mass on its performance. The drying chamber in this dryer is 90 x 90 x 180 cm long; the chimney is 22 cm in internal diameter and 150 cm high; the solar collector covers 180 x 90 cm^2 and is inclined at 20° to the horizontal facing south.

This dryer was used to test the effect of using various transparent material as the collector cover (Fig. 14). Although transparent materials other than glass would be cheaper, the temperatures obtained in the solar collector using polyethylene (plastic) or fibreglass are substantially lower than those using glass and drying was slower. Further work is in progress to assess the advantages of this low cost dryer.

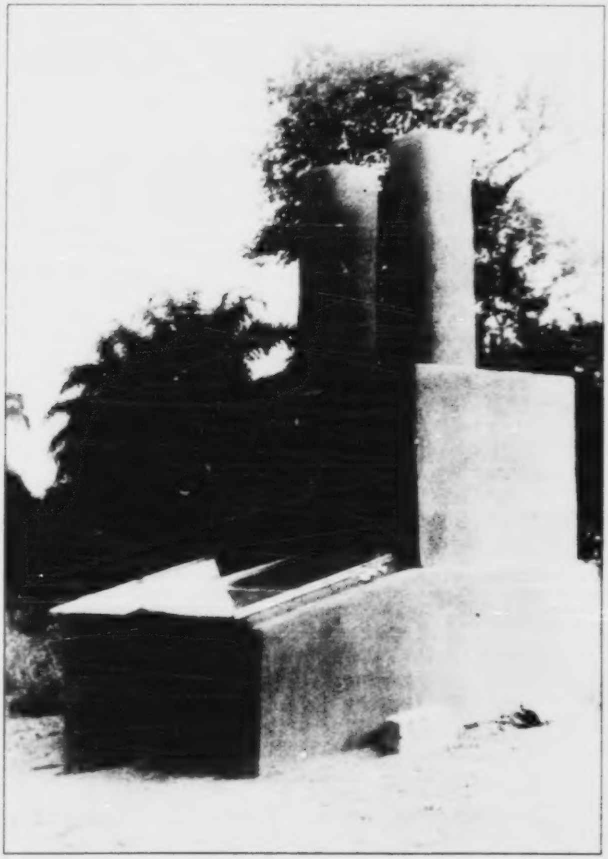


Fig. 13. Natural-convection dryer made from mud bricks.

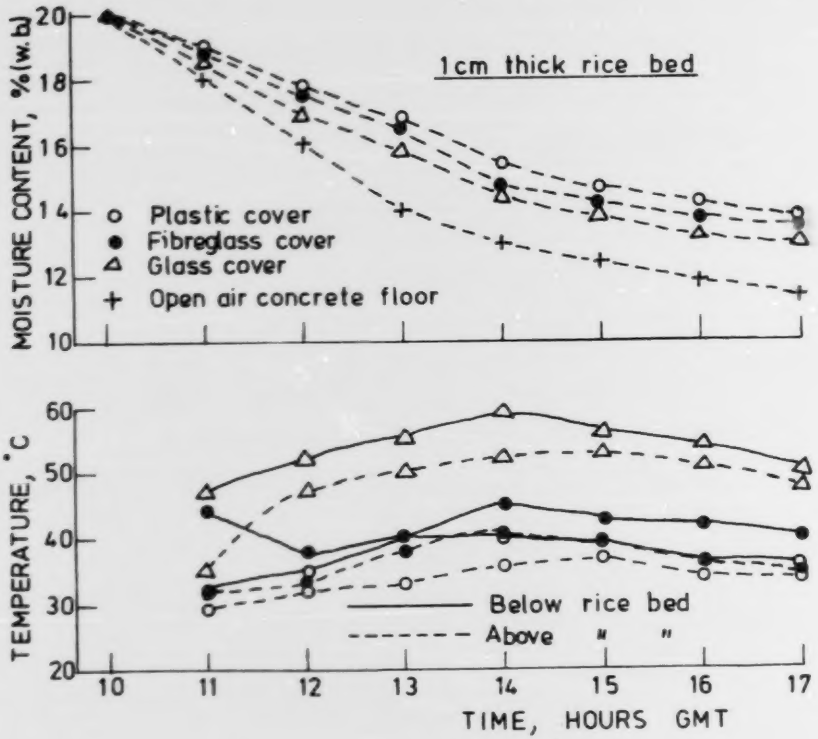


Fig. 14. Dependence of performance of mud brick dryer on type of transparent cover used.

Field Testing

In Sierra Leone, there have been no meaningful tests of solar dryers among the rural farmers: this is also generally true for most other African countries. In some countries, such as in Sierra Leone, research and development (R&D) have not yet produced suitable solar dryer designs whereas, in others, researchers are either reluctant to venture out into villages or are ignorant of what approaches to take.

Assuming that a dryer design has been obtained based on the needs of the intended beneficiaries and the R&D personnel involved have the will to carry out field work, certain basic guidelines must be followed to ensure that the dryer is properly tested under real-life conditions. Experience suggests that, because this activity is interdisciplinary, the team should consist at least of a technologist, a socioeconomist, and one or more extension workers. The choice of the test sites depends on the availability of crops, receptiveness of the beneficiaries to change, and their enthusiasm to participate. Throughout the field testing, the technologist and the socioeconomist should visit the field sites regularly to make spot checks.

Although the list of eight events outlined below is by no means complete, we believe that it gives a framework for carrying out field testing:

- Choose appropriate dryer design;
- Choose sites for field testing with the help of extension workers and socioeconomists;
- Install or build dryers with the active participation of beneficiaries and extension worker;
- Assign extension workers to monitor dryer operation and user reaction;
- Prepare questionnaire to be used during field testing to cover technical performance, economics of drying, and user reaction;
- Allow the user to operate the dryer in comparison with traditional drying. Basic data such as weight of crop before and after drying, and drying time should be collected by extension worker. Testing should ideally last for at least a drying season;
- Modify the drying system, if needed, during field testing; and
- Evaluate the results to assess technical performance, economic viability, and social acceptability.

The importance of field testing within an R&D program should not be underestimated because it is through this activity that a true assessment can be made of the suitability of the developed solar dryer. A substantial effort must be made by African researchers to introduce drying systems among the rural users. Without this intervention, the present situation of having dryers remaining in laboratories can be expected to continue.

Potentially Useful Dryers

The work in Sierra Leone on solar crop drying indicates that it would be more economically advantageous for a dryer to dry more than a single crop during most of the year. However, because solar energy would be inadequate on a year-round basis to produce the required heat, hybrid dryers may, in some cases, be appropriate.

The hybrid solar/sawdust dryer and the natural-convection indirect dryer described here could be developed for use in several countries in Africa. Such developments must, however, be rapid because of the changing economic situation. For example, these two dryers were within the financial reach of some farmers about 5 years ago when they were constructed from plywood, galvanized iron, and glass. Hardly any farmers will buy these dryers today because of the high cost of materials, which have increased 10-fold in some cases.

In Sierra Leone, work is actively in progress to use the indirect solar dryer for drying rice and farm testing is expected by early 1987. However, field tests of the hybrid dryer are not planned because more work is needed to use low-cost materials.

Future Research on Solar Drying

Work carried out in Sierra Leone suggests that further research is needed to improve solar drying. These activities, the assessment of drying needs, laboratory work, and the field testing of prototypes, are outlined in the following sections.

Assessment of Drying Needs

Although a study on the farmers' perception of their drying needs has been carried out in Sierra Leone, further surveys are necessary to obtain a more complete understanding of the drying problem. For example, studies are needed to estimate quantities of crops that must be dried, their geographical distribution, losses in income due to inadequate drying, assessment of the capability and willingness of farmers to acquire a drying system, possible dryer capacities, and the possibility of improving farmers' income through the introduction of improved drying systems.

Because they are multidisciplinary, these initial studies must involve both socioeconomists and technologists. Farmers must also be sensitized to the potential benefits of improved drying.

Laboratory Research

The nutritive values of crops and the effect of drying on both these values and their organoleptic qualities should be studied. Within such research, the optimum drying temperatures and duration of drying needed to achieve the best dried product must be specified for a wide range of crops. Also, the effect of pretreatment on the quality of the crops and their shelf-life deserve attention.

During these studies, close collaboration will be needed between home economists, biochemists, and engineers.

Because it has been shown that measured solar energy data are unavailable and it is simply supplying enough heat for solar drying throughout the drying seasons, research in the following areas should be considered. First, more reliable systems to acquire solar radiation data must be installed in various parts of the country; these systems must be properly staffed and maintained. The data obtained over about 2-3 years can then be used to develop reliable methods for predicting solar radiation values for use in designing dryers. Second, work using the hole-through-sawdust type burner in the hybrid dryer should continue on improving its efficiency and extending the range of agricultural waste that can be used as fuel.

To understand the performance and to improve design procedures for indirect natural-convection solar dryers, laboratory research should be carried out in the following areas:

- To obtain detailed and accurate data on the distribution of temperatures, relative humidities, and pressures throughout the dryer;
- To obtain data on the drying curves for various crops using the depth of loading as a variable parameter;

- To develop simple design procedures for natural-convection dryers using a combination of experimental data and computer modeling;
- To develop dryers using locally available materials, such as mud, clay, galvanized iron, straw, and transparent plastics;
- To determine the effect of using high thermal capacity materials such as mud or clay bricks on the overall performance of the dryer; and
- To improve airflow through the use of heated chimneys, vortex generators, and simple mechanical devices, taking into account their location specificity.

Research methodology for field testing of solar dryers is lacking. Engineers and socioeconomists need to investigate the benefits of several approaches that might be adopted during the introduction of dryers. Some suggestions are:

- To assess the success of field testing due to the involvement of potential manufacturers, extension workers, and farmers (at an early stage);
- To determine the extent of involvement of the users and research team in the operation of the dryers; and
- To determine suitable monitoring procedures to adopt, specifying timing and the role of each person.

Strategy for Achieving Results

The general lack of human and material resources in Africa suggests that collaboration is necessary among researchers. Research on solar drying should be carried out in a more coordinated manner to maximize the use of the available resources. Certain suggestions that may help to promote the use of solar dryers are outlined below.

Network on Drying

The existing group of projects on drying should be formed into an effective network. Organizations such as the Commonwealth Science Council and the International Development Research Centre may be able to play a leading role in coordinating the activities of such a network. Each researcher should, depending on expertise, concentrate on a well-defined problem. In this way, duplication of efforts would be kept to a minimum and research activities would be complementary.

Publication of Results

Results of work done on drying are not usually circulated to a wide readership. Even when results are available, it is often difficult to assess the contribution of the research because of style of presentation, clarity, or lack of information. Researchers working on problems of relevance to Africa should be encouraged to make their findings available to fellow researchers through effective communication. A network on drying could coordinate the distribution of such valuable information.

Conclusion

This paper has attempted to present a critical assessment of requirements, conditions, and equipment for solar drying in rural areas in Africa using investigations in Sierra Leone as examples. The following four conclusions can be made:

- Initial needs-assessment studies are a prerequisite for the wide-scale adoption of improved drying systems.
- Solar drying research needs the involvement of personnel from various disciplines.
- Natural-convection solar crop dryers can be used effectively but substantial research and development work is needed before appropriate systems can be obtained. Main areas for future work are design with the help of modeling and experimentation followed by field testing.
- Investigations on solar drying in Sierra Leone have obtained results that have made useful contributions to the knowledge of operation of natural-flow solar dryers.

Acknowledgments -- The research reported in this paper was funded by research grants from the International Development Research Centre, Canada, and the United Nations Industrial Development Organization.

References

Ali, H.M., Sakr, I.A. 1982. Drying of vegetables in Egypt. In Yaciuk, G., ed., Food drying. International Development Research Centre, Ottawa, Ont., Canada. IDRC-195e, 15-19.

Ba, A., Banzet, C., Degbe, J.M. 1982. Drying onions in Niger. In Yaciuk, G., ed., Food drying. International Development Research Centre, Ottawa, Ont., Canada. IDRC-195e, 61-62.

Bassey, M.W. 1982a. Influence of chimney configuration on temperatures in a solar dryer. In Proceedings of Energex 82 Conference, Regina, Canada. Vol II/II, 862-867.

——————— 1982b. Potential use and performance of indirect free convective solar crop dryers in Sierra Leone -- Final report, IDRC Research Project 3-P-78-0113. Department of Mechanical Engineering, University of Sierra Leone, Freetown, Sierra Leone.

——————— 1982c. Solar energy as a heat source in crop drying in Sierra Leone. In Yaciuk, G., ed., Food drying. International Development Research Centre, Ottawa, Ont., Canada. IDRC-195e, 73-80.

——————— 1983a. Characteristics of hole-through-sawdust type burners. International Journal of Ambient Energy, 4 (1), 39-46.

——————— 1983b. The use of sawdust for small-scale energy applications (Chapter 66). In Meyer, R.F., Olson, J.C., ed., The future of small energy resources. McGraw Hill Publishers, New York, NY, USA.

____________ 1985a. Interaction between temperatures, airflow and chimney design in indirect free convective solar dryers. In Proceedings of the International Conference on Research and Development of Renewable Energy Technologies in Africa, Mauritius (Vol. II). Commonwealth Secretariat, London, U.K.

____________ 1985b. Design and performance of a hybrid crop dryer using solar energy and sawdust. In Proceedings of INTERSOL 85 Conference, Montreal, 22-28 June 1985. International Solar Energy Society, Victoria, Australia.

Bassey, M.W., Massaquoi, J.G., Sesay, J. 1978. A recommended formula for predicting total solar radiation in Sierra Leone. Paper presented at the 11th Biennial West African Science Association Conference, 13-18 March 1978, Lome, Togo.

Gomez, M.I. 1982. Effect of drying on the nutritive value of foods in Kenya. In Yaciuk, G., ed., Food drying. International Development Research Centre, Ottawa, Ont., Canada. IDRC-195e, 31-35.

Johnston, J.C. 1984. Solar crop drying in Zimbabwe. In Proceedings of the Solar Energy Society of Zimbabwe Conference: Making Use of Renewable Energy, Harare, Zimbabwe. Professional Conferences, Zimbabwe PVT Ltd., Harare, Zimbabwe. p. 62-65.

N'Jai, A.E. 1985. Report of tests on use of solar-tents for fish drying in the Gambia. In Proceedings of the International Conference on Research and Development of Renewable Energy Technologies in Africa, Mauritius (Vol. II). Commonwealth Secretariat, London, U.K.

Okoh, I.K.A. 1985. Solar drying of timber in Liberia: Determination of the efficiency of an experimental solar dryer based on temperature measurements. In Proceedings of the International Conference on Research and Development of Renewable Energy Technologies in Africa, Mauritius (Vol. II). Commonwealth Secretariat, London, U.K.

Oosthuizen, P.H., Preston, E.G.A., Bassey, M. 1985. Numerical simulation of a natural convection solar rice dryer. In Proceedings of the 7th Miami International Conference on Alternative Energy Sources, Miami, Florida, 9-11 December 1985. pp. 505-508.

Othieno, M.W. 1985. Optimization of solar air heating collectors used for crop drying. In Proceedings of the International Conference on Research and Development of Renewable Energy Technologies in Africa, Mauritius (Vol. II). Commonwealth Secretariat, London, U.K.

Sebbowa, F.B. 1985. Design considerations and prototype tests on a pyrethrum flow solar energy dryer. In Proceedings of the International Conference on Research and Development of Renewable Energy Technologies in Africa, Mauritius (Vol. II). Commonwealth Secretariat, London, U.K.

Whitfield, M.J.C.C. 1985a. Improving mass flow rates in free convective dryers. In Proceedings of the International Conference on Research and Development of Renewable Energy Technologies in Africa, Mauritius (Vol. II). Commonwealth Secretariat, London, U.K.

———————— 1985b. Limiting performance and potential of free convective solar crop dryers in Sierra Leone -- Interim report, IDRC Research Project 3-P-83-0107. Department of Mechanical Engineering, University of Sierra Leone, Freetown, Sierra Leone.

A NUMERICAL MODEL OF A NATURAL-CONVECTION SOLAR GRAIN DRYER: DEVELOPMENT AND VALIDATION

P.H. Oosthuizen[1]

Abstract *-- This study was designed to develop a simple but reliable computer model of a natural-convection solar grain dryer, to validate this model as far as possible against existing experimental results for solar rice dryers, and to carry out a series of laboratory-scale experiments that would provide results that could be used in improving the computer model. The model is based on the assumption that all minor pressure losses are negligible in comparison with the pressure drop across the rice bed:. thus, the net buoyancy force just balances the pressure drop across the rice bed. It is also assumed that the air leaving the rice bed is either saturated or at a temperature equal to the initial rice temperature and that, as a result, the buoyancy forces all effectively occur in the air below the rice bed. The model has been validated against available experimental results and good agreement between the predicted and experimental results were achieved. Some computer exploration of the effect of dryer dimensions on its performance has been undertaken. The apparatus and instrumentation to be used in a laboratory study of dryer performance are described.*

Introduction

Although the drying of rice is still accomplished in many countries by spreading it in a thin layer on the ground on a hard surface, it is widely acknowledged that significant reductions in losses during drying could be achieved by replacing this method by some form of indirect natural-convection solar rice drying. In a typical dryer of this type (Fig. 1), the rice bed is contained within a drying chamber and air, which is heated in a simple flat-plate solar collector, is drawn through the drying chamber by the buoyancy forces resulting from the temperature difference. Many attempts have been made to develop such natural-convection solar rice dryers (see, for example, Bassey 1982; Whitfield 1985; Yu Wai Man and Wong Too Yeun 1984) but the results achieved with these dryers have not generally been satisfactory. One of the reasons for the relatively poor performance is that these past studies have generally relied heavily on a purely experimental approach and no extensive theoretical investigations of the designs were undertaken before the dryers were

---

[1] Department of Mechanical Engineering, Queen's University, Kingston, Ontario, Canada.

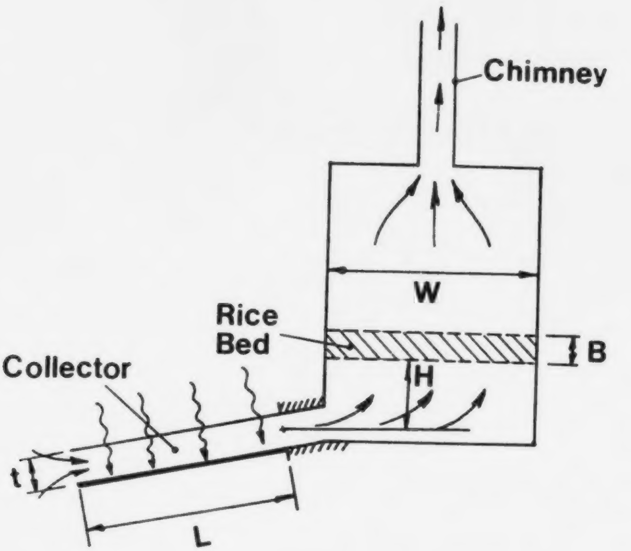


Fig. 1. Type of dryer being considered.

constructed. One consequence of this is that no clear means of improving the performance of the dryer could be deduced from the results. Another reason for the continued poor performance of these dryers is that the testing of the dryers has often been carried out in a relatively uncontrolled manner so that the reasons for the poor performance could not be clearly deduced from the results.

To assist in the design of improved solar rice dryers, the present study, therefore, sought:

- To develop a simple but accurate model of indirect natural-convection solar crop dryers that can be used in developing more efficient dryer designs;
- To validate the model, as far as possible, against existing experimental results obtained with natural-convection solar rice dryers;
- To undertake a series of controlled experimental laboratory studies of the basic characteristics of a natural-convection crop dryer and to use these results to improve the numerical model; and
- To use the final numerical model to design an improved indirect solar rice dryer.

In the study, the need to carry out both numerical studies and highly controlled experimental studies that support each other has been accepted as vital to the improvement of dryer performance.

This paper is primarily concerned with the first two points in the list. The basic approach used in the experimental study is, however, also outlined and some possible improvements in dryer design are discussed briefly. Although this paper is concerned primarily with rice drying, the computer model can be applied to the drying of some other similar crops with relatively minor modification.

Model Equations

The computer model has two basic sections. The first section determines the solar insolation and the second calculates the performance of the dryer when subjected to this insolation. If the application of a given dryer in a particular geographical area is being considered, then section 1 will generate insolation values corresponding to the selected geographical area. If, on the other hand, experimental results and the results given by the model are being compared, the insolation values used by the program will be the actual values measured during the tests. Because this paper deals basically with the second problem, that is, a comparison between experimental and numerical results, it is assumed that the insolation is a known input. If the first type of problem is being considered, however, the insolation values for a particular geographical location can be determined using the method described by Preston (1985). The model described here is essentially the same as that described by Oosthuizen (1986).

A dryer of the type shown in Fig. 1 has been considered. When the air enters the collector, there is a pressure drop due to the acceleration of the fluid. There are also pressure losses in the collector and in the chimney, at the exit of the collector, at the entrance to the chimney, and across the rice bed. These pressure losses are matched by the buoyancy forces that occur because the air in the collector and in the chamber is at a higher temperature than the ambient air. When the order of magnitude of all the losses is considered, the pressure drop across the rice bed is found to be the dominant pressure drop; thus, in the present model, all other pressure losses are assumed to be negligible compared with that across the rice bed. When this assumption is made, it is, of course, necessary that the net buoyancy forces just balance the pressure drop across the rice bed. It is assumed in the present model that the pressure drop across the rice bed (Δp) is proportional to the velocity of the air through the bed:

$$\Delta p = Ub/K \qquad [1]$$

where

U = mean air velocity in dryer
b = thickness of rice bed, and
K = bed pressure drop coefficient.

It should be noted that, because the pressure drop across the rice bed is by far the dominant pressure loss in the dryer under operational conditions, experimental studies of unloaded dryers give little information about how the dryer will actually perform.

The buoyancy forces must next be considered. These will, of course, be proportional to the difference between the mean air temperature in the section of the dryer considered and the ambient air temperature. Now, as will be discussed later, the air leaving the rice bed is at or only slightly above the temperature of the rice bed. Therefore, because the rice bed and ambient air temperatures remain close, the contribution of the buoyancy force from the air above the bed will be negligible. It should be noted that this means that the chimneys that are so often fitted to natural-convection rice dryers will have little effect on the dryer performance unless the solar heating of this chimney is significant. Because the chimneys are usually vertical, the solar heating of the chimney will usually be very small unless the dryer is being used far from the equator. This is also another reason why experimental studies that use unloaded dryers or dry rice give little information about how the dryer will actually perform because, under these conditions, all the air in the drying chamber and chimney is at a higher temperature than the ambient air. As a result of this assumption, the buoyancy forces are assumed to occur only in the collector and in the dryer chamber below the rice bed. In the collector, the air is heated from ambient temperature to that of the collector exit and the buoyancy force in the collector is given approximately by using the mean temperature in the collector. Hence, the net buoyancy force (NBF) will be given by:

$$\mathrm{NBF} = \beta g \rho (T_c - T_a)(L \sin \theta/2 + H) \qquad [2]$$

where

β = bulk coefficient of expansion of air
g = gravitational acceleration
ρ = kinematic viscosity of air
T_c = temperature of air leaving collector
T_a = ambient air temperature
L = length of collector
θ = angle of inclination of collector, and
H = height of rice bed above collector outlet.

This buoyancy force must, in view of the assumptions above, just balance the pressure drop across the rice bed. Hence, equations 1 and 2 together give

$$Ub/K = \beta g \rho (T_c - T_a)(L \sin \theta/2 + H) \qquad [3]$$

If we consider an energy balance for the solar collector, the rate of enthalpy gain of the air in passing through the collector must just equal the rate of solar energy gain:

$$\rho U_c W_c B_c c_p (T_c - T_a) = \eta q_I W_c L \qquad [4]$$

where

U_c = mean air velocity in collector
W_c = width of collector
B_c = collector gap size
c_p = specific heat of air
η = collector efficiency, and
q_I = insolation.

This can be rearranged to give the temperature rise across the collector as

$$T_c - T_a = \eta q_I L \ / \ \rho U_c B_c c_p \qquad [5]$$

The mean velocities in the collector and in the drying chamber are, of course, related by mass continuity requirements so that

$$U = U_c \ (W_c B_c / W W_D) \qquad [6]$$

where

W = width of drying chamber and
W_d = length of drying chamber.

Equations 4 and 5 contain the collector efficiency (η) as a variable. For conventional types of collectors, this efficiency, as shown in standard textbooks (see, for example, Sayigh 1978), is given approximately by

$$\eta = C_1 - C_2 \ (T_p - T_a) \ /q_I \qquad [7]$$

where

C_1 and C_2 are constants and
T_p = temperature of collector plate.

Because there must be a balance between the rate at which the collector plate absorbs solar energy and the rate of heat transfer from the plate to the air passing through the collector, it follows that

$$\eta q_I W_c L = h W_c L (T_p - T_a) \qquad [8]$$

where

h = heat-transfer coefficient between collector plate and air.

It should be noted that the effective heat-transfer coefficient (h) is based on the frontal area of the collector. For a simple flat-plate collector, it will be equal to the mean heat-transfer coefficient; however, if more complex collector plates are used, it will include the effects of the increased heat-transfer area. It should also be noted that h is based on the difference between the temperatures of the plate and the ambient air. Equations 7 and 8 together give

$$\eta = C_1 h / (C_2 + h) \qquad [9]$$

Thus, the collector efficiency at which the dryer operates will depend on the value of h. If h is very large, its effect on η will be small but, at small values of h, η will be strongly dependent on h becoming directly proportional to h as h tends to zero.

The value of h will depend, in general, on the geometry of the collector, the mean velocity of the air through the collector, and the buoyancy forces in the collector. For a natural-convection dryer with a simple flat-plate collector, if the buoyancy force effects on the flow in the collector are small, the flow in the collector will tend to be laminar and of a boundary layer type and boundary layer theory then indicates that h should vary as the square root of the Reynolds number based on the mean air velocity and the length of the collector. It has, therefore, been assumed that

$$h = h_0 \, (Re_L/5000)^{0.5} \qquad [10]$$

where

h_0 = heat-transfer coefficient that would exist with a Reynolds number of 5000 and

$Re_L = U_c L/\nu$.

Once the values of the required constants are specified, these equations are sufficient to define the induced velocity through the dryer for any insolation value (q_I). An iterative solution procedure must be used because h depends on the velocity. In this procedure, a value of h is assumed and a flow rate is calculated. This allows Re_L to be found and an improved h value can then be determined and the whole procedure repeated until convergence is achieved.

So far, the generation of the hot airstream that will be used to dry the rice has been considered. The rice drying itself must now be considered. Consideration of the available experimental results and of a previous relatively unsuccessful attempt at modeling the performance of a natural-convection solar rice dryer (see Oosthuizen et al. 1985; Preston 1985) suggests that a very simple model of the drying process can be adopted. In this model, it is assumed that all the water to be removed from the rice is held in the rice in the liquid form and, therefore, that the thermal energy in the airstream entering the rice bed is used, basically, to supply the latent heat required to evaporate the water from the rice. As a result of this assumption, there will be little change in the rice-bed temperature during drying and its thermal capacity can, therefore, be ignored. As a further consequence of this assumption, the temperature of the air leaving the rice bed will be at or only slightly above the initial rice-bed temperature, which will be close to the ambient air temperature. It is this fact that allows the buoyancy forces in the air above the rice bed to be ignored.

To determine the drying rate, we must consider the drying processes indicated on a psychometric chart (Fig. 2). If the air leaving the collector and entering the drying chamber, and therefore entering the rice bed, is at the temperature indicated by a point such as b, then the drying rate will be limited by the available sensible heat of the incoming air, i.e., by the fact that the air leaving the rice bed will be at the rice-bed temperature (as indicated by point b in Fig. 2) and not fully saturated. Because the available sensible heat in the airstream will be equal to the energy it gains in the solar collector, the drying rate for this situation will be determined by

$$\eta q_I W_c L = m_r \, (dM/dt) \ell \qquad [11]$$

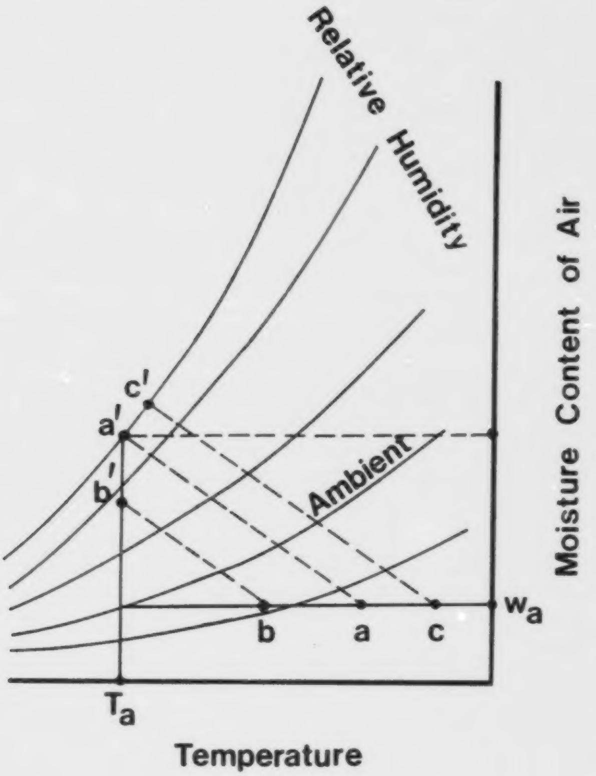


Fig. 2. Possible changes in temperature and humidity in the rice bed.

where

m_r = mass of dry rice in bed
M = moisture content of rice on dry basis
t = time, and
ℓ = latent heat of water.

The left hand side of equation 11 is, of course, the net rate at which solar energy is being absorbed by the collector and transferred to the air passing through the dryer. The right hand side is the rate at which latent heat is being supplied to the bed.

If, however, the air leaving the collector is at a point such as c (Fig. 2), the drying rate will be limited by the fact that the air leaving the bed will be saturated (i.e., the point c' must lie on the 100% relative humidity line). In this case, the drying rate is determined by noting that the energy balance for the collector gives

$$\eta q_I W_c L = m\, c_p\, (T_c - T_a) \qquad [12]$$

where

m = air mass flow rate through dryer

whereas the energy balance for the rice bed requires that

$$m\, c_p\, (T_c - T_o) = m\, (w_o - wa)\ell \qquad [13]$$

where

T_o = temperature of air leaving rice bed
w_o = moisture content at exit of rice bed, and
w_a = moisture content at ambient conditions.

It is convenient to rewrite equation 13 as

$$(c_p/\ell\ )\ [(T_c - T_a) - (T_o - T_a)] = w_o - w_a \qquad [14]$$

Because the saturation line on the psychometric chart defines w_o as a function of T_o, equations 12 and 14 together allow T_o and w_o to be determined for any value of the insolation (q_I). The drying rate is then obtained by considering a moisture mass balance for the rice bed that gives

$$m_r\, (dM/dt) = m\, (w_o - w_a) \qquad [15]$$

In all real cases, T_o will be only slightly above the rice bed temperature.

This model of the drying process will only apply, of course, as long as the moisture content in the rice bed remains well above the equilibrium moisture content for the ambient conditions. Once the moisture content drops to near the equilibrium moisture content, the drying rate will start to be limited by the moisture diffusion rate within the rice grains as well as by energy considerations and a much more complex drying model must be adopted. However, because drying can be regarded as complete when the equilibrium moisture content is reached, this is not a serious limitation. In applying the model then, these equations are used until the moisture content (M) has dropped to a value equal to the equilibrium moisture content at ambient conditions and M is then assumed to remain constant at this value.

Computer Implementation

A computer model based on these equations has been developed for an indirect natural-convection solar rice dryer of the type shown in Fig. 1. In addition to the dimensions of the dryer, this program requires, as inputs, values for the relative humidity and temperature of the ambient air, the bed pressure loss factor (K), the rice density (ρ_r), and the collector performance parameters (C_1, C_2, and h_o). In addition, the variation of the insolation (q_I) with time is required. As discussed earlier, q_I could be either given from measurements obtained during experimental studies or generated by a geographical model of the type described by Preston (1985).

In applying the model, the following values have been assumed:

$K = 0.0005\ \mathrm{m^2/Pa}$ per second
$\rho_r = 600\ \mathrm{kg/m^3}$
$C_1 = 0.56$
$C_2 = 4.31\ \mathrm{W/m^2}$ per °C, and
$h_o = 8\ \mathrm{W/m^2}$ per °C.

The values C_1 and C_2 used are typical of those observed experimentally for simple dryers with relatively poor quality glass covers (e.g., Sayigh 1978). The value of h_o used is based primarily on the flat-plate laminar boundary-layer result with rough account being taken of the effects of buoyancy forces and of fluid acceleration through the collector. Both of these effects tend to increase the convective heat transfer coefficient. The values of K and ρ_r used are taken from Excell (1980).

In the actual model, at each time for which a q_I value is specified, the equations in the previous section can be used to solve for the drying rate, dM/dt, at that time. The moisture content at time Δt later is then obtained using a simple finite difference approximation; that is,

$$M_{(t + \Delta t)} = M_t + (dM/dt)_t \Delta t \qquad [16]$$

Using this value of M, the process is repeated for the next time step and so on to give the variation of moisture content with time. As mentioned earlier, this procedure is only applied until M has dropped to the equilibrium moisture content, which is taken here to be approximately equal to 12%, and M is then assumed to remain constant at this value.

Model Validation

Before the computer model can be used with any confidence to design an improved rice dryer, its ability to adequately predict the performance of a dryer must, of course, be proven, i.e., the model must be validated. This has been done by comparing the results given by the model with the experimental results obtained with loaded dryers that are presented by Bassey (1982) and Whitfield (1985). One of the difficulties encountered in undertaking this comparison arose from the fact that, in Bassey's paper, the variation of the insolation with time was only partially specified for some of the days over which the tests were performed and, in Whitfield's, although some insolation values were given for all days over which the tests were undertaken, these values are for only a portion of each day. In specifying q_I, then, some assumptions concerning the form of its variation during the day had to be made. It was assumed that, in all cases, a 10-hour drying day occurred, i.e., that there was significant insolation for 10 hours/day. Using this assumption and whatever measured values of q_I were given, assumed insolation variations were derived (Fig. 3). For the test results given by Bassey, the same isolation variation was assumed for each day on all days on which tests were undertaken (Fig. 3, broken line). However, because more extensive measurements of q_I are given by Whitfield, it was possible to describe separate insolation variations for each of the days over which the test was undertaken (Fig. 3, solid line).

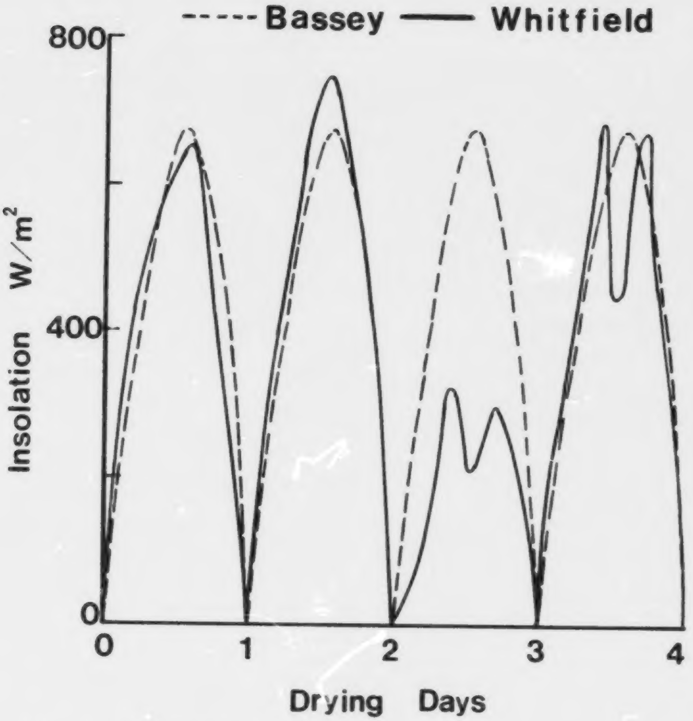


Fig. 3. Assumed daily variation of insolation based on data from Bassey (1982) and Whitfield (1985).

In carrying out all of the model validations, average constant values of 30°C for ambient air temperature and 50% for relative humidity were assumed and the rice-bed temperature was assumed equal to this mean ambient air temperature. The initial moisture content of the rice was deduced in each case from the experimental results. Rewetting of the rice during the night was neglected.

Using these assumptions, the computer model has been used to predict the variation of the moisture content with time for the four loaded dryer tests for which results are given by Bassey (1982) and for the single loaded dryer test for which results are given by Whitfield (1985). Comparisons between these predicted variations and the measured results are shown in Figs 4-7 (the full set of results are given elsewhere, Oosthuizen 1986).

In assessing the agreement between the predicted and experimental results, it must be realized that there appear to be occasional problems with the moisture content determination in the experimental studies. Whether this was caused by the sampling procedure used, as suggested by Bassey et al. (this volume), the method used to store the samples before the moisture content was measured, or with the method

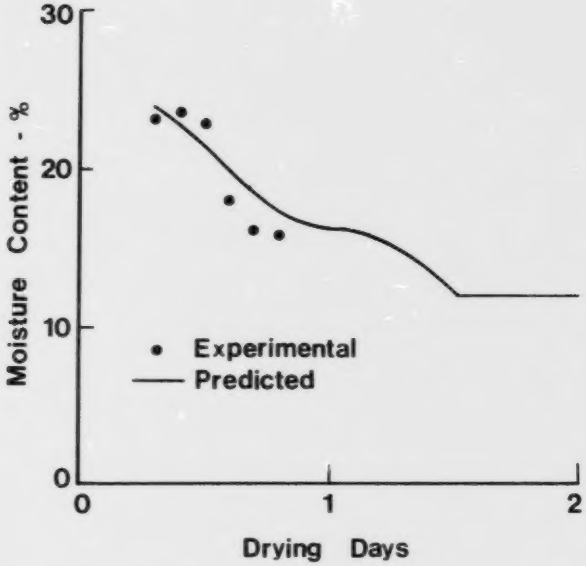


Fig. 4. Comparison of predicted and experimental results (Bassey 1982) for a rice bed thickness of 25 mm.

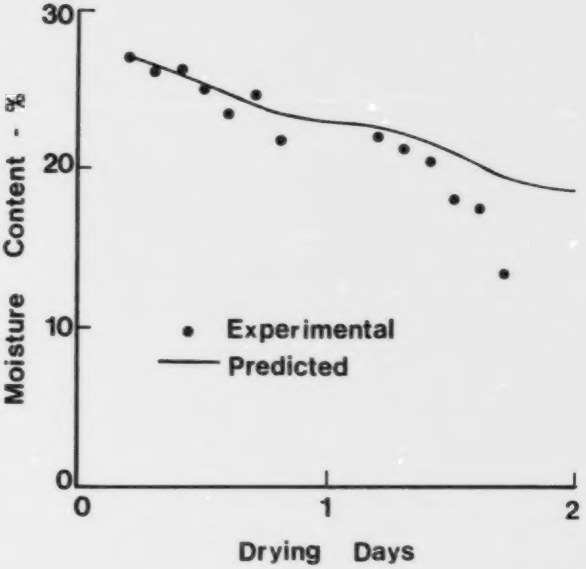


Fig. 5. Comparison of predicted and experimental results (Bassey 1982) for a rice bed thickness of 50 mm.

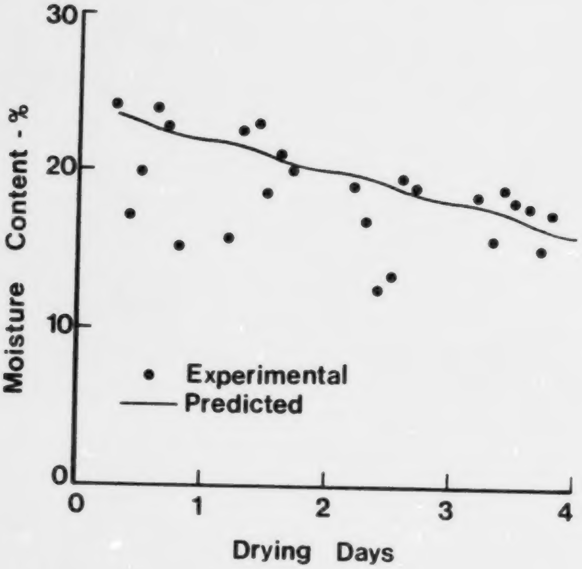


Fig. 6. Comparison of predicted and experimental results (Bassey 1982) for a rice bed thickness of 100 mm.

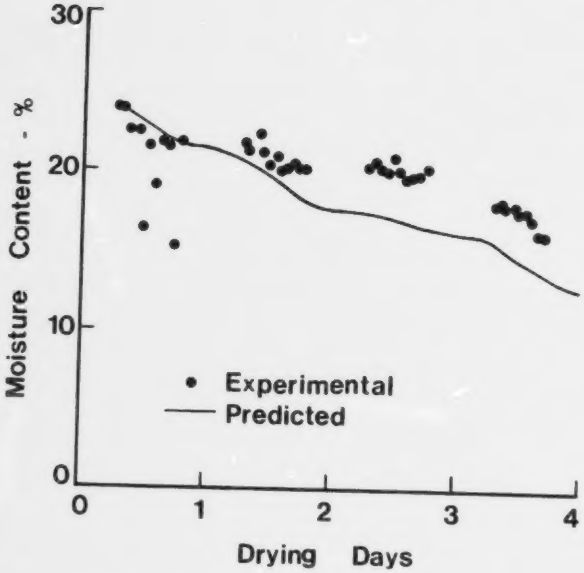


Fig. 7. Comparison of predicted and experimental results (Whitfield 1985).

used to determine the moisture content cannot be determined. However, the very low moisture content values periodically observed in the experimental studies, some of them being close to the equilibrium moisture content, are obviously in error. If these points are ignored, the agreement between the model and the experimental results is quite good. Thus, although the results from some much more controlled experiments are required to refine the model, it does appear capable, even in its present form, of indicating some improvements that can be made in existing dryer designs.

Improved Dryer Design

An assessment of the results obtained during the model validation strongly suggests that the most important factors that limit the performance of the existing dryers were

- The size of the collector and
- The height of the rice bed above the collector outlet.

The dryers used in the experimental studies described by Bassey (1982) and Whitfield (1985) had, basically, a collector that was 0.7 x 0.7 m with the gap between the collector plate and the glass cover of about 40 mm and a dryer chamber that was about 0.9 x 0.9 m in cross section with the rice bed roughly 0.12 m above the collector plate.

In assessing the effect of changes on the dryer's performance in the two dryer parameters mentioned above, calculations were undertaken for the following fixed values: dryer chamber cross-sectional size, 1 x 1 m; collector gap, 40 mm; rice-bed thickness, 75 mm (about 45 kg of rice); ambient temperature, 30°C; ambient relative humidity, 50%; and initial rice moisture content, 25%. The insolation values used were the same as those given in Fig. 3 for Bassey (1982). It has been assumed that the collector length and width are, in all cases, equal. The height of the rice bed above the collector outlet has, for reasons discussed later, been taken as 1 m.

As is to be expected, the dryer performance is considerably improved as the collector size increases (Fig. 8) and, with a 1 x 1 m collector, successful drying is accomplished in just over 2 days: this would be satisfactory in most applications. These, and other calculations, suggest that a rough design guide is to make the collector area equal to the area of the rice bed.

A study of the effect of the height of the rice bed above the collector outlet (H) on dryer performance (Fig. 9), using a 1 x 1 m collector, showed significant improvements in dryer performance with increasing H up to values of 1 m. However, relatively little improvement in performance was found for H values greater than 1 m.

In conclusion, then, it is suggested as a preliminary design guide that for dryers with rice-bed thicknesses up to about 100 mm:

- The area of the collector be set equal to the rice-bed area;
- The rice bed be placed 1 m above the collector outlet; and
- No chimney be fitted to the dryer.

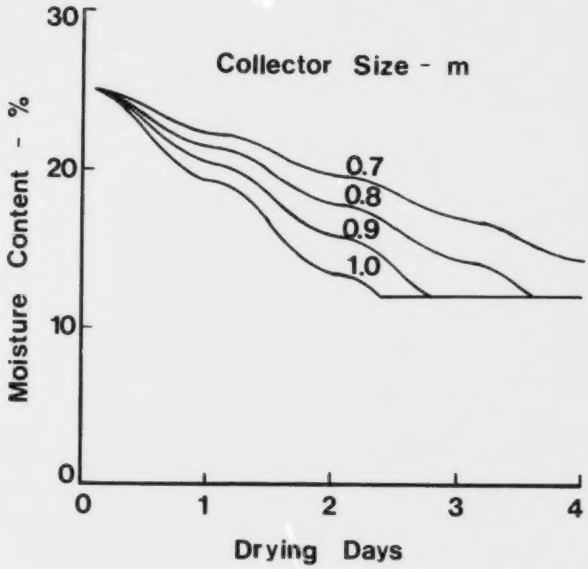


Fig. 8. Effect of collector size on dryer performance.

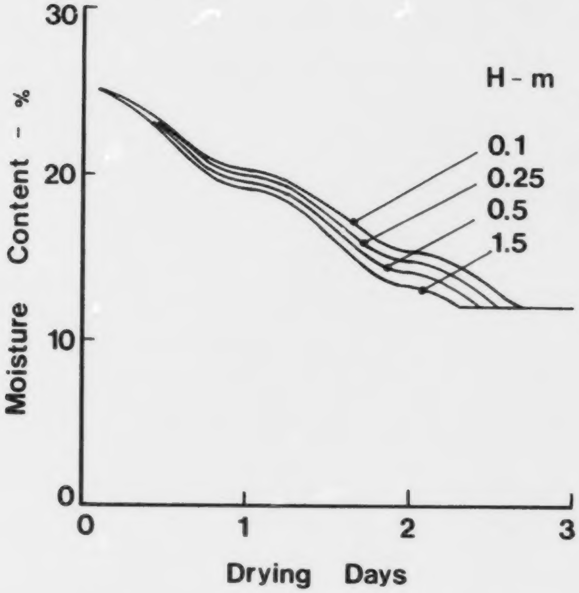


Fig. 9. Effect of rice bed height on dryer performance.

Experimental Study

Although the results given by the computer model agree quite well with the experimental results, there are some significant differences that may be the result of deficiencies in the model. It is suspected that, if such deficiencies exist, they are most probably due either to errors in the assumed heat-transfer coefficient in the collector or to deficiencies in the rice-drying model used.

To check whether these aspects of the model do, in fact, need improvement, a series of controlled laboratory-scale experiments is being undertaken. These experiments use a model of a typical natural-convection solar rice dryer, but with a simulated solar collector. This simulator consists of an aluminum plate with a series of electrical heaters beneath it (Fig. 10). The following measurements are taken during the test with the instrumentation indicated:

- The average temperature of the collector plate measured using a series of copper-constantan thermocouples attached to the back of the plate;
- The air temperature before and after the rice bed measured with thermocouple probes inserted into the airstream;
- The pressure drop across the rice bed measured using pressure taps in the dryer wall in conjunction with a Barocel electronic manometer system;
- The weight of the dryer with the rice measured by mounting the entire dryer on three load cells; and
- The ambient air temperature and relative humidity.

The measurements are obtained automatically using a Sciemetric Data Acquisition unit in conjunction with a Zenith Z-150 microcomputer.

It was felt that an adequate comparison between the numerical model and the experimental results could only be made if the pressure drop factor (K) for the actual rice being used in the dryer was known. For this reason, separate tests are undertaken in which air is blown at a known rate through a rice bed of known thickness. With the K value accurately determined in this way, the measured pressure drop across the rice bed in the dryer tests can be used to find the flow rate through the dryer. With the flow rate known, using the measured air temperatures before and after the collector and the mean plate temperature, the heat-transfer coefficient for the collector can be found using:

$$m\, c_p\, (T_c - T_a) = hA_p\, (T_p - T_a) \qquad [17]$$

where

A_p = area of collector plate.

Using the measured variation of total dryer weight with time and the known mass of rice on a dry basis, the variation of rice moisture content with time can be found.

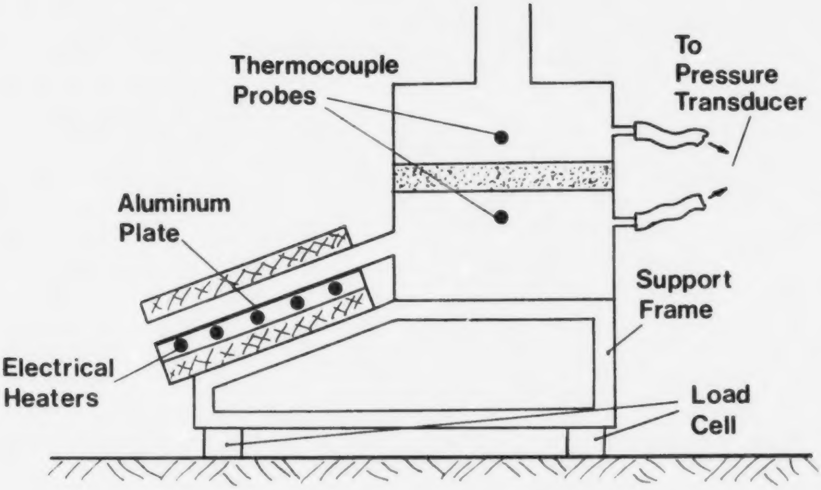


Fig. 10. Layout of experimental apparatus.

Conclusions

On the basis of the model validation tests, five main conclusions were reached. First, the collector area should be set equal to the area of the rice bed in the dryer; second, the dryer bed should be placed at a height of roughly 1 m above the collector outlet; third, tests with no load in the dryer give little information about dryer performance; fourth, a chimney is not likely to produce much improvement in dryer performance; and, fifth, all of the basic rice dryer performance parameters can be measured automatically using a simple microcomputer-based data-acquisition system.

Acknowledgments -- This work was supported by the International Development Research Centre of Canada.

References

Bassey, M.W. 1982. Potential use and performance of indirect free convective solar crop dryers in Sierra Leone -- Final report, IDRC Research Project 3-P-78-0113. Department of Mechanical Engineering, University of Sierra Leone, Freetown, Sierra Leone.

Excell, R.H.B. 1980. Basic design theory for a simple solar rice dryer. Renewable Energy Review Journal, 1 (2), 1-14.

Oosthuizen, P.H. 1986. A numerical study of the performance of natural convection solar rice dryers. Paper presented at the Fifth International Drying Symposium, Cambridge, Massachusetts, 13-15 August 1986.

Oosthuizen, P.H., Preston, E.G.A., Bassey, M. 1985. Numerical simulation of a natural convection solar rice dryer. In Proceedings of the 7th Miami International Conference on Alternative Energy Sources, Miami, Florida, 9-11 December 1985. pp. 505-508.

Preston, E.G.A. 1985. Simulation of a natural convection solar rice dryer. Queen's University, Kingston, Ont., Canada. MSc thesis (Eng.).

Sayigh, A.A.M. 1978. The technology of flat plate collectors. In Dixon, A.E., Leslie, J.D., ed., Solar energy conversion -- an introductory course. Pergamon Press, Toronto, Ont., Canada. pp. 101-124.

Whitfield, M.J.C.C. 1985. Limiting performance and potential of free convective solar crop dryers in Sierra Leone -- Interim report, IDRC Research Project 3-P-83-0107. Department of Mechanical Engineering, University of Sierra Leone, Freetown, Sierra Leone.

Yu Wai Man, Y.K.L., Wong Too Yeun, R.T.T. 1984. Solar crop drying. African Energy Programme, Commonwealth Science Council, London, U.K. Technical Report.

Appendix

A_p = area of collector plate
B_c = collector gap size
b = thickness of rice bed
C = constants in collector equation
c_p = specific heat of air
g = gravitational acceleration
H = height of rice bed above collector outlet
h = heat-transfer coefficient between collector plate and air
h_o = value of h at $Re_L = 5000$
K = bed pressure drop coefficient
L = length of collector
ℓ = latent heat of water
M = moisture content of rice on dry basis
m_r = mass of dry rice in bed
m = air mass flow rate through dryer
q_I = insolation
Re_L = $U_c L/\nu$
T_a = ambient air temperature
T_c = temperature of air leaving collector
T_p = temperature of collector plate
T_o = temperature of air leaving rice bed
t = time
U = mean air velocity in dryer
U_c = mean air velocity in collector
W = width of drying chamber

W_c = width of collector
W_D = length of drying chamber
w_a = moisture content at ambient conditions
w_o = moisture content at exit of rice bed
β = bulk coefficient of expansion of air
Δp = pressure drop across rice bed
η = collector efficiency
θ = angle of inclination of collector
υ = kinematic viscosity of air
ρ = density of air
ρ_r = density of rice in bed

SOLAR DRYING PROBLEMS IN TOGO

K. Amouzou, M. Gnininvi, and B. Kerim[1]

Abstract -- *Solar drying tests conducted at the Laboratoire sur l'énergie solaire of the University of Benin are described, together with models of developed dryers. Three types of dryer, with load capacities ranging from 15 to 2000 kg, are described from the standpoint of both efficiency and economic profitability, with particular emphasis on the drying of maize, which is one of the main products of Togo. Economic analysis shows that, for full-time dryer usage, the solar dryer compares favourably with the oil- or charcoal-fired industrial dryers. For the actual conditions of dryer usage in our country, it appears that none of these systems is economically very profitable, because the cost of drying is between 19 and 32% of the value of maize at harvest. In terms of financial costs, as opposed to economic costs, the charcoal-fired system is the least costly and the solar system the most costly.*

Introduction

Arable land in Togo is being increasingly exploited in an attempt to achieve food self-sufficiency. In 1980, 550,000 ha, or 22% of the total agricultural area, were under cultivation. By 1985, the figure had risen to 670,000 ha, or 27%.

This policy of food self-sufficiency has led to an increase in food-crop production, and about 250,000 t of maize, 150,000 t of millet and sorghum, and 40,000 t of rice are now harvested annually. The surplus production is dried using simple traditional methods, based only on direct absorption of the incident solar radiation by the products themselves.

Aside from their intrinsic interest, these traditional techniques are nevertheless responsible for considerable product losses and have a number of inherent deficiencies, including: the photo-oxidation of some nutrients and destruction of vitamins during drying; the relatively slow drying process, which allows mildew to develop especially in humid and rainy regions; and the risk of rewetting of the products, either through condensation and formation of dew during the night or through rainfall.

---

[1] Laboratoire sur l'énergie solaire, Université du Bénin, Lomé, Togo.

In an effort to improve drying efficiency, the Laboratoire sur l'énergie solaire, Université du Bénin (LESUB) initiated a program in 1980 to develop simple solar dryers.

In this paper, we first describe briefly the climatic conditions that prevail at cereal harvest, then we examine the efficiencies of the dryer models tested and the results of the drying tests, and finally the problems that we believe remain to be solved if high quality dried products are to be obtained.

Climatic Data

The climate of Togo ranges from subequatorial with four seasons in the south, to tropical with two seasons and low rainfall in the north. Average solar conditions prevail in the subequatorial climate, which is generally characteristic of the west coast of the Gulf of Benin. Meteorological data indicates about 2090 hours of annual sunshine in the south and 2660 hours in the north. The highest sunshine is experienced between October and April, with a daily average is 7.2 hours and a total solar radiation intensity of 4.5 kWh/m^2 per day at the ground. The least sunny months are June-September, which have a daily average of 5.5 hours and a solar intensity of 4.4 kWh/m^2 per day.

Mean values of insolation and solar energy at the ground for 1980-85 are presented in Tables 1 and 2 for three locations representing the north, centre, and south of the country (Fig. 1). The relative humidity (RH) of the ambient air is very high, 90-100% during the night (dew point 25°C) and 50-60% at noon in good weather. These climatic conditions are most unfavourable for traditional drying. The cereal crop, especially maize, is harvested during the rainy season, which has the least amount of sunshine during the year. The products dry slowly, especially in the south of the country, and they are susceptible to diseases and rotting. Also, their moisture content barely reaches an acceptable level for storage. These disadvantages could be alleviated through the use of solar dryers that allow better control of drying.

LESUB Dryer Models

The dryers tested were designed using the classic principle of the greenhouse effect, and were of mixed type. Solar rays penetrate the glass surface and heat the black-painted absorber inside the collector; the drying air is heated by the black surface and circulates by natural convection. As it passes up through the product to be dried, it gathers water vapour and finally escapes through the chimneys. The product is dried by the combined action of the incident solar radiation and the hot air from the preheating collector.

Brace-type Solar Dryer

Our Brace-type dryer is portable and made of wood and plywood (Fig. 2). It is 1.12 m long, 1.30 m wide, and 0.67 m high, and its collector area is about 1 m^2. The absorber is made of galvanized sheet metal painted black. Airflow at the dryer inlet is regulated by two screened slots. The drying chamber has a volume of 0.13 m^3 and

Table 1. Monthly average total normal radiation at ground level, 1980-85.

			Lomé		Atakpamé		Mango	
Month	G[a]	E[b]	M[c]	V[d]	M	V	M	V
January	9.2	4.2	3.7	16	4.0	10	4.4	10
February	9.8	5.2	4.5	11	4.5	9	4.8	9
March	10.0	5.5	4.8	13	4.6	15	4.9	15
April	10.2	5.6	5.3	20	4.8	16	4.9	14
May	10.0	5.5	4.8	29	4.7	18	4.7	19
June	9.7	4.5	3.9	34	4.3	19	4.5	22
July	9.9	4.3	4.0	27	3.7	23	4.1	23
August	10.0	4.2	4.2	24	3.6	25	3.9	26
September	10.1	4.8	4.8	14	3.9	20	4.4	22
October	9.8	5.3	4.8	17	4.6	16	4.7	13
November	9.4	5.3	4.8	16	4.4	10	4.2	9
December	9.1	4.7	3.7	15	3.6	11	4.0	11
Mean			4.4	20	4.3	16	4.5	16

[a] G = theoretical value of radiation above the atmosphere (kWh/m^2 per day).

[b] E = radiation value estimated by Thompson (1970) based on a network of 10 stations throughout the African continent (kWh/m^2 per day).

[c] Li-Cor silicon cell instrument (kWh/m^2 per day ± 5-10%).

[d] V = Percent standard deviation from the mean.

can dry 10-15 kg of product in 3 days. The moisture-laden air is exhausted through two chimneys, each 1.5 m high. The cost of the dryer in 1980 was 30,000 XOF[1].

This simple dryer was used for a long time to dry malt in the Centre de nutrition de Cacaveli in Lomé, and to dry medicinal plants at the Antenne régionale de nutrition. Drying tests were also conducted on salt fish and okra. Dehydration is progressive and effective in 4 days (Gnininvi 1981).

The wooden frame was not weather-resistant (rain or wind), and the problem of waterproofing arose. Its useful life was 4 years. This first model was used mainly as a prototype on which to measure physical parameters.

Multipurpose Cement Solar Dryer

The multipurpose cement dryer was the same shape as the Brace-type but made from breezeblock instead of wood (Fig. 3). It is 4.82 x 2.82 m and has a load capacity of 80-100 kg. Its characteristics are:

---

[1] In 1986, 220 francs of the Communauté financière africaine (XOF) = 1.00 Canadian dollar (CAD).

Table 2. Mean values of insolation and energy, Lomé, 1980-85.

Month	Insolation (hr/day) [X]	Energy (kWh/m^2 per day) [Y]	Correlation (r)	Regression[a]			Brightness index[b]
				a	b	± $\sigma y/X$	
January	6.7 (32)[c]	3.7 (19.1)	0.47	0.16	2.68	0.63	0.40
February	7.4 (24)	4.5 (14.6)	0.56	0.20	3.03	0.54	0.45
March	7.0 (32)	4.8 (19.8)	0.79	0.33	2.50	0.58	0.48
April	7.6 (37)	53.0 (23.0)	0.83	0.35	2.59	0.68	0.52
May	6.5 (56)	4.8 (31.1)	0.77	0.32	2.78	0.96	0.48
June	4.8 (69)	4.0 (35.8)	0.78	0.33	2.37	0.55	0.41
July	4.8 (65)	4.0 (30.1)	0.86	0.33	2.41	0.61	0.41
August	5.2 (56)	4.3 (30.4)	0.85	0.37	2.32	0.68	0.43
September	6.1 (46)	4.8 (25.5)	0.71	0.30	2.96	0.84	0.48
October	7.0 (42)	4.9 (24.2)	0.58	0.23	3.29	0.98	0.50
November	8.1 (23)	4.8 (18.2)	0.69	0.32	2.21	0.63	0.51
December	6.9 (29)	3.7 (19.6)	0.65	0.23	2.09	0.56	0.40

[a] $Y = aX + b \pm \sigma y/X$; variabilities are given for a confidence interval of 69% ($\sigma y/x = \sigma y (1 - r^2)^{0.5}$.

[b] Energy received at ground divided by theoretical energy above atmosphere (Duffie and Beckman 1980).

[c] Values in parentheses are variation (±) as percentage.

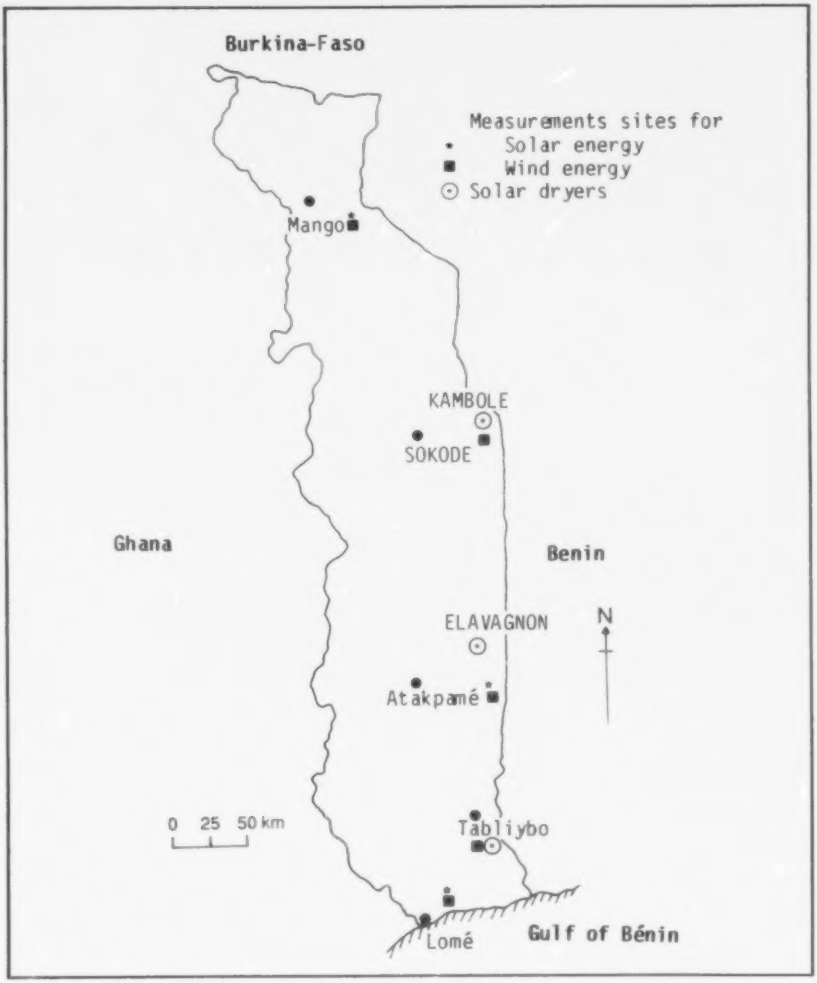

Burkina-Faso
Measurements sites for
• Solar energy
■ Wind energy
⊙ Solar dryers
Mango
KAMBOLE
SOKODE
Ghana
Benin
ELAVAGNON
N
Atakpamé
0 25 50 km
Tabliybo
Lomé
Gulf of Bénin

Fig. 1. Experimental stations in Togo.

- Both the collector for preheating the air and the drying chamber are covered with nine glass panes 1.33 x 0.48 m. To reduce the cost of the absorber, the black metal sheet was replaced with charcoal, a product that is available in rural areas. The thermal exchange surface was increased in an attempt to compensate for the poor absorption characteristics and the hygroscopic properties of charcoal.

- A layer of gravel (2.4 m^3 of 40 cm thickness) is placed at the preheated air inlet to ensure good thermal storage.

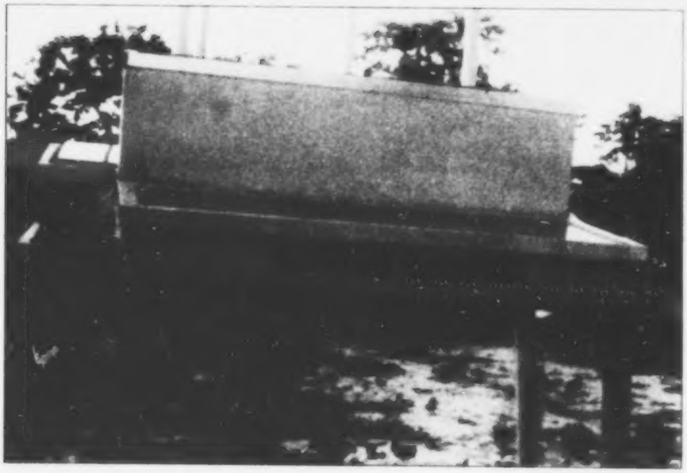
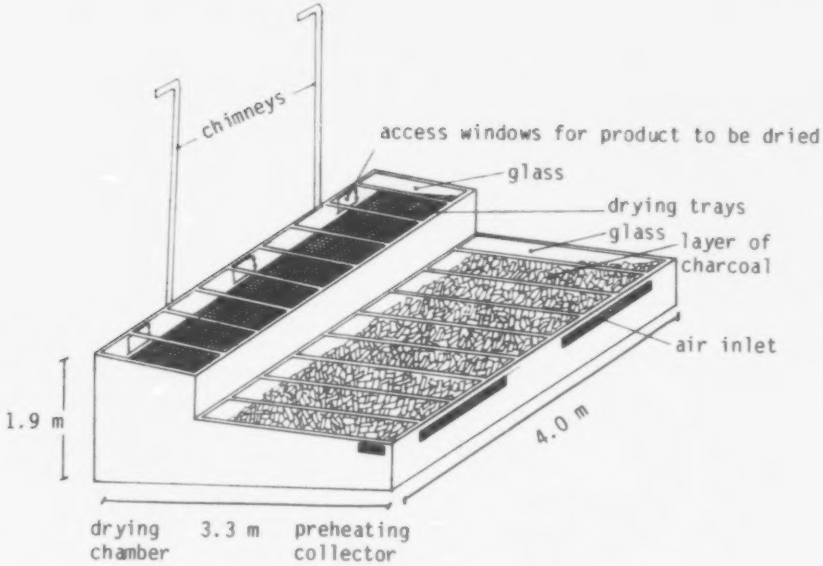


Fig. 2. Brace-type wooden solar dryer.



chimneys
access windows for product to be dried
glass
drying trays
glass
layer of charcoal
air inlet
1.9 m
4.0 m
drying chamber
3.3 m
preheating collector

Fig. 3. Cement solar dryer of 80-100 kg capacity (1981).

- Two screened openings of 1.49 x 0.14 m each at the preheater collector inlet face the direction of the prevailing winds (southwest side).
- Five drying trays made of fine wire mesh provide a total drying surface of 5 m^2.
- Three access doors on the north side allow for loading the product to be dried.
- There are two chimneys made of polyvinylchloride (PVC) piping, 3 m high and 20 cm diameter.
- The whole system is inclined at 15° (latitude of site: 6°N).
- The total glassed surface is 10.56 m^2.

Efficiency

Measurements on this dryer show that temperatures of 65°C can be obtained at 1200 hours in good weather in the drying chamber (700-800 W/m^2) as opposed to 40°C in open air (Table 3). The relative humidity in open air was almost 45%, but only 30% in the dryer.

The mean air speed inside the drying chamber varied between 0.15 m/sec at 0800 hours and at 2000 hours, when the outside wind speed was 1 m/sec, and 1.2 m/sec at 1200 hours when the outside wind speed was 3.5 m/sec. The air speed in the drying chamber and outside was virtually zero between 2000 hours and 0700 hours (Fig. 4).

The volume flow rate inside the chamber thus increased gradually from 2.6 m^3/hour in the morning to 31.2 m^3/hour at midday and returned to 2.6 m^3/hour by the end of the afternoon.

Products Dried

The drying tests were conducted on cassava strips, which had an initial moisture content of 60%. At the end of the 1st day of drying, the moisture content of the product in the dryer was much less than in

Table 3. Variation of temperature and relative humidity with time of day in the cement solar dryer (80-kg load)

Physical parameters	**Dryer**	**Open Air**
Mean temperature (°C)		
at 0800 hours	32	28
at 1200 hours	65	40
at 1700 hours	43	27
Relative humidity (%)		
at 1200 hours	30	45
at 1700 hours	41	55

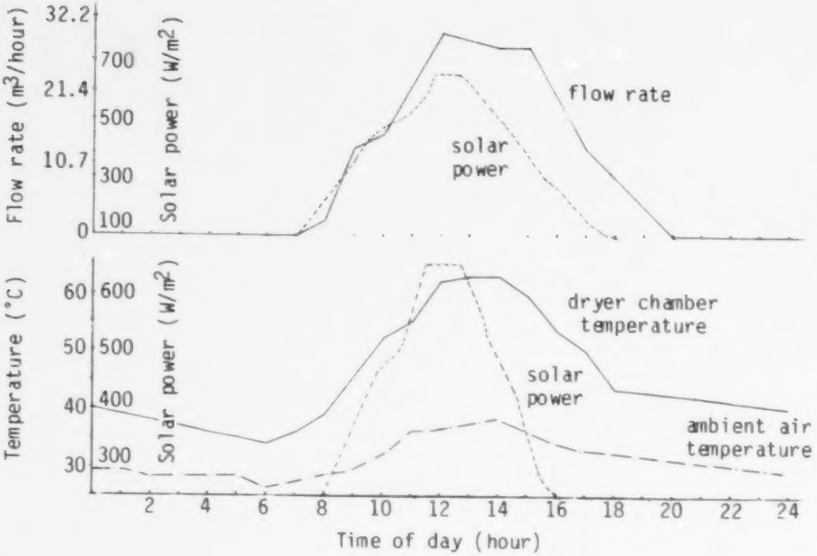


Fig. 4. Variation of air volume flow rate, dryer chamber temperature, and solar power as functions of time of day (unloaded dryer).

open air (44 vs 52%; Fig. 5). After 4 days, the residual humidity level of the product was 9.9% in the dryer against 11.6% in open air. A comparative study of drying of these strips in the solar enclosure and in the open air was presented at the Nairobi Seminar in November 1983 (Gnininvi and Kerim 1983).

Tests were also conducted on maize grain (initial moisture content of about 20%, dry weight basis) in a 5-cm thick layer. Drying was progressive and, after 3 days, the moisture content of the grain inside the dryer was 12% as opposed to 15% in open air (Table 4).

Two problems were apparent: the doors proved to be too small for access to the drying surface, especially when the products were being turned over manually; and once the strips of cassava were spread out, rust spots quickly appeared on the metallic mesh of the trays.

Irrespective of the atmospheric conditions, the temperature in the drying chamber barely exceeded 70°C, which is the recommended value for good drying of cassava or maize (CEEMAT 1974). This dryer model has been operational since 1981 and no problems have been encountered with regard to either the watertight seals on the collectors or deterioration of the walls. Its total cost was about 400,000 XOF. No attempt has been made to popularize the dryer in the rural community, because its load capacity is too small for collective use.

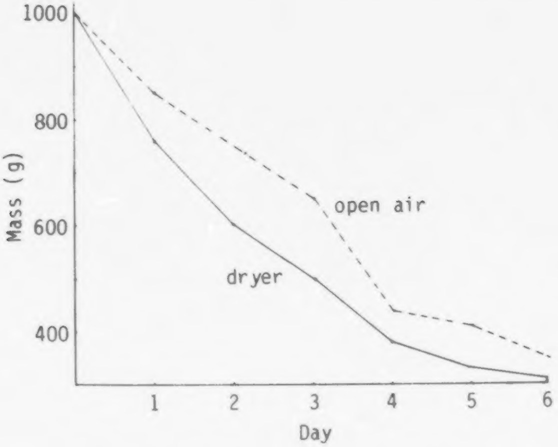


Fig. 5. Drying curves for cassava.

Table 4. Drying of maize grain.

	Initial moisture content	Day					
		1	2	3	4	5	6
Grain moisture content (%)							
Dryer	20.3	16.1	13.2	12.0	11.8	13.1	12.2
Open air	20.3	19.0	16.8	15.0	17.6	18.5	18.6
Ambient RH (%)		77	90	73	80	94	89

Cement-type Dryer

The cement-type dryer (Fig. 6) is a semi-industrial dryer with a load capacity of 2000 kg of cereals and is intended for use by a cooperative of several producers or at a cereal collection centre. It was constructed essentially using local materials.

Several improvements were made in its design based on the performance of the prototype.

- Black-painted gravel was used for the absorber instead of charcoal. Gravel is not hygroscopic like charcoal, but has a much greater thermal inertia. Also, it is available in rural areas.
- The area of the preheating collectors was doubled so that temperatures higher than ambient could be maintained even during the

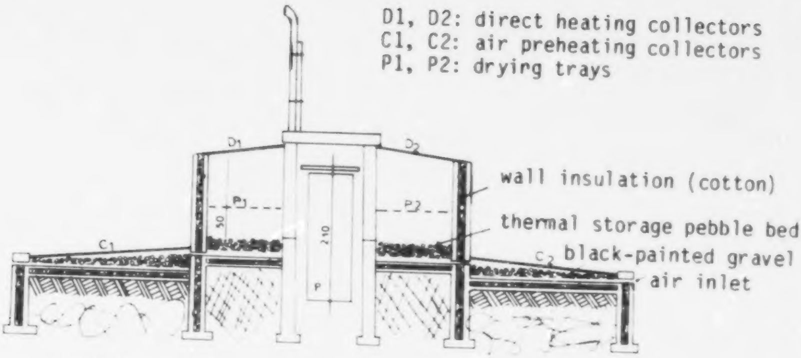

D1, D2: direct heating collectors
C1, C2: air preheating collectors
P1, P2: drying trays
D1
D2
P1
P2
50
210
P
C1
C2
wall insulation (cotton)
thermal storage pebble bed
black-painted gravel
air inlet

Fig. 6. Cross-section of solar dryer capable of holding 2000 kg of cereals (maize).

night. In this regard, it was recognized that the upper collectors were to provide direct drying whereas the lower collectors were used mainly to allow thermal storage.

- A symmetrical arrangement was adopted for the overall design, so that the dryer could be oriented with one preheating collector facing south and the other facing north. This was a valid option because of the low latitude of the country (6-10°N). The advantage of this orientation is that it reduces the wall surface area that is exposed to the prevailing wind, and hence the heat loss. In addition, the symmetrical design allowed a central passageway to be added in the drying chamber to facilitate product loading.
- The gravel bed of the preheating collector, which absorbs and stores part of the energy, was above the air inlet to obtain better heat distribution.
- Other features were a capacity of 2000-2500 kg of cereals (30% moisture content); drying surface of 32 m^2 on aluminum trays; collector surface of 81 m^2; and access through two doors, one at each end of the drying chamber. The cost was about 5 million XOF.

Performance

The maximum and minimum temperatures recorded inside the drying chamber during the rainy season were 60 and 28°C, respectively, compared with 35 and 22°C in open air.

The RH of the air inside the dryer was always below 60%, even though the ambient RH sometimes reached 100% (Fig. 7). These measurements were taken under no-load conditions.

Utilization

Three dryers of this type were installed at rural sites (Fig. 1). They were first used for a series of tests in the presence

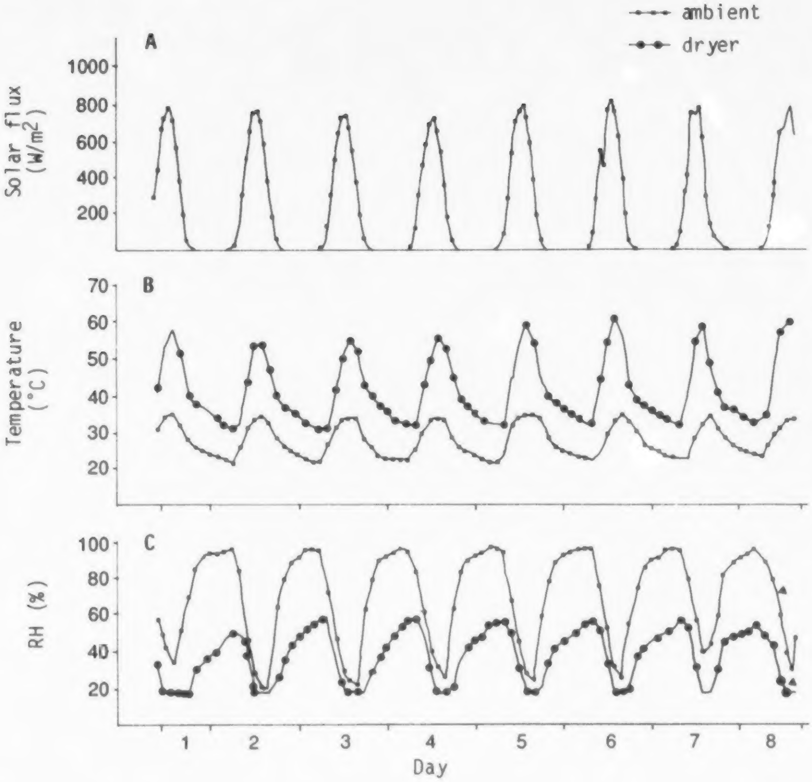


Fig. 7. Measurements of performance of the solar dryer (load capacity 2000 kg) under no-load conditions.

of potential users. The tests were done on commercial maize with an initial moisture content of about 20% (dry weight basis). The product was spread out on drying trays to a depth of 5-8 cm and sampled at the end of each day to determine the moisture loss. After the 2nd day, the moisture content started to oscillate, indicating that the drying limit imposed by the equilibrium conditions of the ambient humidity had been reached (Figs 8 and 9).

The physical parameters recorded during the operation showed that drying occurred for a temperature difference between the inside of the chamber and the ambient of 20-25°C maximum and 10°C minimum (Fig. 8a and b). (These results were presented at the International Conference on Research and Development on Renewable Energy Technologies in Africa held in Mauritius in March 1985 (Gninivi et al. 1985).)

Conclusions

Designed to operate by natural convection, the "cement" dryer is suitable for drying cereals having a low initial moisture content,

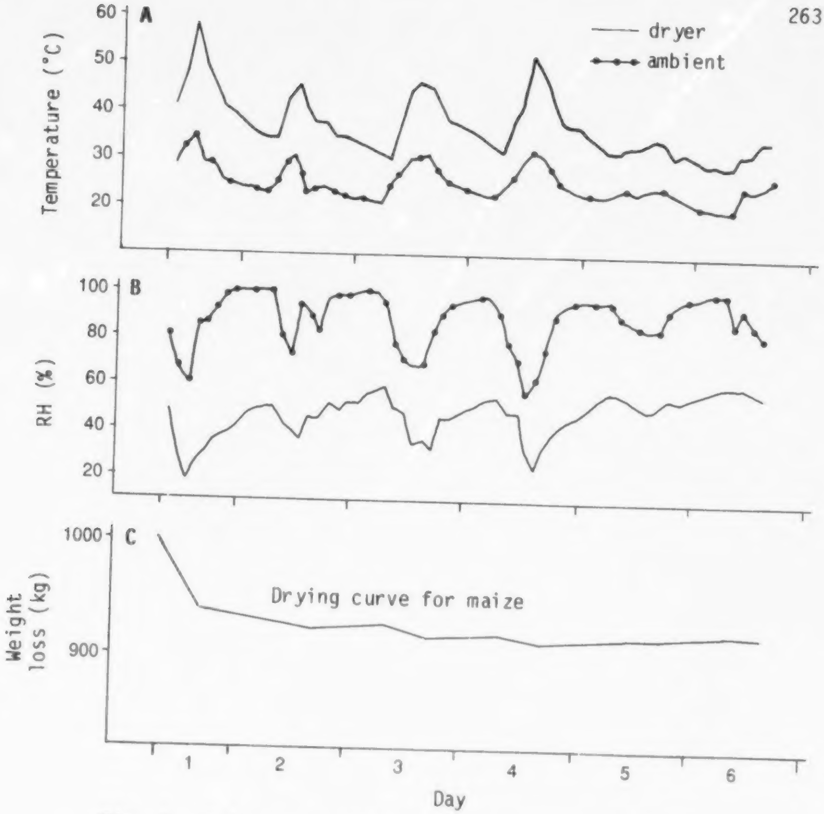


Fig. 8. Maize grain drying: solar dryer at Tabligbo.

between 25 and 30%. It could also be used for drying cassava or yam strips, vegetables, or fish if a plastic mesh were used for the drying surface instead of the metallic mesh. However, the load would have to be two to three times less. To improve the convective flow of ambient air, fans could be installed in the chimneys.

At an investment cost of 5 million XOF, this dryer would fall within the price range of other dryers that operate satisfactorily in some countries such as Brazil or Colombia.

As far as maintenance is concerned, the glass was frequently broken either by objects falling on the collectors or possibly because of the excessive mechanical stresses imposed on the cheap glass (known as photographic glass).

As a follow-up to the operation, a campaign was organized by the laboratory each year at harvest to demonstrate and publicize the equipment. The dryer attracted much interest in Tabligbo (Fig. 1), which is one of the centres of collection of cereals for delivery to Togograin (the agency charged with purchasing surplus cereals at the

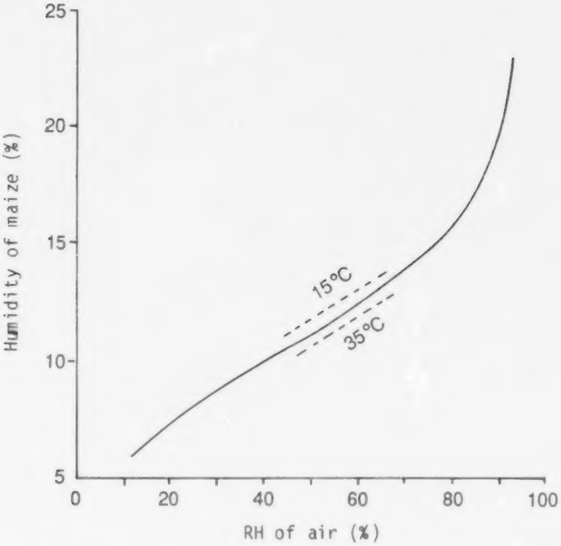


Fig. 9. Equilibrium humidity curve for maize in air at 25°C (CEEMAT 1974).

time of production, and with drying, storing, and distributing the product on the national market).

Socioeconomic Constraints

Simple solar dryers designed for better control of drying can only be effective if they are accepted by users. However, these installations, once left in the users' charge, are often neglected, despite all recommendations on care and maintenance. The glass is damaged and routine maintenance (removal of dust from the collectors and general cleaning around the dryers) is irregular. The users have no sense of responsible ownership because the dryers were installed free on a provisional experimental basis.

This attitude probably stems from the fact that the actual use of the dryer is barely 4-6 weeks during the year. Outside the harvesting season, the question of responsibility for maintenance arises, particularly with dryers intended for agricultural cooperatives, which frequently have management problems or internal conflicts and are, therefore, unstable or ephemeral.

We believe that, to raise their sense of responsible ownership, future users should be required to participate, either by contributing equipment or labour, during construction of solar dryers in rural regions.

To reduce the risk of breakage, the glass panes should be replaced by a more resistant material. Tests are currently underway on collectors covered with transparent plastic, both ultraviolet-stabilized and unstabilized, which can retain a transparency greater than 85% for an extended period.

From an economic standpoint, a dryer with a load capacity of 2 t of cereal (3 days of drying) is capable of drying 4 t/week, or 24 t during the 6-week harvest period. Over a 10-year period, 240 t could thus be dried. On this basis, for an installation cost of 5 million XOF and without allowance for investment discount, the cost of drying 1 t of cereal would be 20,800 XOF. This is a high value in relation to the current market price of the product, which sells for 50,000-100,000 XOF/t.

If the dryer were used year-round (52 weeks), the cost of drying 1 t would be 2200 XOF, or 10% of the present cost. To realize this price, multipurpose dryers would have to be developed or the dryers would have to be used only for drying high-value products, such as spices, medicinal plants, or rare foodstuffs.

The long drying times for solar dryers (2-4 days) compared with the relatively short drying times of oil-fired dryers (several hours) constitutes a serious impediment to their popularization.[1] To reduce the drying time, four major improvements would be required.

- The efficiency of the collectors should be increased. The nature of the absorber surface significantly influences efficiency, particularly at high temperatures (>60°C) (COMES n.d.). Selective surfaces can improve the efficiency of collectors, but they are of little interest when the dryers are not run at high temperature. Efficiency can also be improved through the use of suitable transparent covers. Because glass is too fragile, research should be directed to evaluating plastics for unattended use in rural areas.

- Thermal losses must be reduced. This could be done by optimizing the architectural design of installations according to the latitude of the region.

- The airflow must be increased to ensure rapid drying. The Centre d'études et d'expérimentation du machinisme agricole et tropical (CEEMAT) has developed a "temperature-airflow" relationship that is recommended for drying maize from 25% to 13% moisture content (with a maximum heterogeneity 3%) (Table 5). Fans should be used where natural convection is inadequate.

Dryer Construction

The dryer collectors should be made of corrosion-resistant material because corrosion has the greatest impact on useful life. The attachments for the collector covers should be corrosion-resistant

---

[1] A comparative analysis of efficiency and cost of solar systems relative to oil- or charcoal-fired systems is given in the appendix.

Table 5. Temperature-airflow relationship for maize drying from moisture content of 25% to 13% (CEEMAT 1974).

Temperature of hot airflow (°C)	**Specific airflow (m^3/hour per m^3 of maize)**
45	2000
60	3000-3500
80	4000-4500
100	5000-6000

and weatherproof. The covers for the collectors should also be easily removable to ease maintenance.

Research in our laboratory is aimed at developing simple solar dryers for the individual operator, i.e., dryers that are adequate for drying the products of one farmer's field. We believe that it might also be possible to use semipermanent installations that are less costly, similar to small greenhouses covered with removable polyethylene so as to allow natural solar drying. Experiments conducted on such installations in other countries such as Mali and Senegal could be studied in the context of the climatic conditions in Togo. Collaboration with these countries in this field would be welcomed.

Dried Products

The product to be dried is not inert. Its physical and biochemical properties impose constraints and boundaries that should not be crossed (Herbert et al. 1984). Tropical products are often poorly understood and their characteristics (temperature, moisture content, etc.) in relation to drying must be specified (Table 6) and accounted for in designing multipurpose solar dryers. It is well known that, for good drying, the surface tension of the water in the product must be higher than the surface tension of the water in the ambient air. On contact with hot air, the water in the product diffuses from the inside toward the outside. The speed of diffusion should be taken into account in determining the drying speed of each product to avoid "overdrying" at the surface. Overdrying can lead to the formation of crusts on the grain, amylolysis in cassava strips, reduction in the germinal power of cereals, and nonenzymic browning (Wallace et al. 1973).

Before drying the product, some preprocessing may be undertaken: cutting of the product into quarters (banana) or strips (cassava and yam); blanching to inhibit enzymes and thus prevent enzymic browning; and preventive treatment against microorganisms. To avoid photooxidization and vitamin destruction, the maximum conditions supportable by each product (temperature-time relationship) should be defined.

Once the products are dried, they must be preserved during storage -- also a thorny problem. In parallel with the drying tests, technical studies should be undertaken on storage under the climatic conditions of our subregion.

Table 6. Specifications for drying agricultural products (Herbert et al. 1984).

Product	Moisture content (%)		Drying temperature (°C)	Preprocessing
	Initial	Final		
Bananas	80	15	70	Cutting
Garden peas	80	5	65	Blanching
Onions, garlic	80	4	55	Cutting
Vegetables[a]	80	10	-	Cutting
Potato	75	13	70	Cutting
Sweet potato	75	7	75	Cutting
French bean	70	5	75	Blanching
Cassava	62	17	70	Cutting
Coffee	51	11	-	Fermentation
Groundnuts	40	9	-	-
Copra	30	5	-	Cutting
Maize	25	13	60-80	-
Cocoa beans	-	9	-	-
Cotton seed	-	9	-	-

[a] Leaves (e.g., spinach or cassava leaves).

In Togo, the agency responsible for regulating cereals has had preservation problems in the storage silos: losses have been between 5 and 100% of the stored product. Research has shown that cereals shipped to Togograin for storage had a moisture content above 13%. The officers of this organization have been forced to redry the product using the costly process of forced convection in dryers fired by fossil fuels.

At LESUB, a work program is being developed aimed at using solar energy for improving large-scale maize storage.

The fundamental reason for the poor quality of grain stored in the present silos seems to be the high humidity of the ambient air. The fact that the temperature is also high (dew point 25°C) results in an increased rate of deterioration. The principle of our proposed solution is to keep the temperature in the silos 15°C higher than the ambient so as to reduce the relative humidity of the air to below 70%, a value that is considered to be the maximum threshold for good maize storage (Tollier and Guilbot 1973; CEEMAT 1974).

Conclusion

Although the merit of solar dryers is recognized (Action 1980; Djamessi 1984), we believe that a prudent approach is nevertheless advisable.

- Dryers that are already in place (Fig. 1) should be monitored for 3-4 years before their operation, efficiency, economic profitability, and useful life are assessed.

- The profitability of individual or collective dryers can only be assured to the extent that they are used year-round.

- To promote natural or forced-convection solar drying, one must study not only sunshine and insolation, but also ambient humidity and wind speed during the drying period. This knowledge will provide a better understanding of the characteristics of the drying power of air, which is necessary for specific dryer design.

- To promote user acceptance of solar dryers, drying times must be reduced and load capacities increased. Dryers will also have to be made more weather-resistant to prolong their useful life.

- Consultation programs (workshops or symposia) should be expanded to allow comparison of existing models and to promote interest among junior researchers. These dialogues should involve biochemists and food engineering specialists who can contribute to defining the characteristics of products during drying.

References

Action/Peace Corps/UITA. 1980. Small farm grain storage: Vol. 3, drying methods. Food and Feed Grains Institute, Manhattan, KA, USA. Research Report.

CEEMAT (Centre d'étude et d'expérimentation du machinisme agricole et tropical). 1974. Séchage et stockage: manuel de conservation des produits agricoles tropicaux -- techniques rurales en Afrique. CEEMAT, Antony, France.

COMES (Commissariat à l'énergie solaire). n.d. Séchage solaire: évolution des énergies renouvelables pour les pays en développement. Éditions SEMA, France.

Djamessi, A. 1984. Développement de séchoirs solaires en Afrique de l'Ouest: Mission de consultant sur le développement des séchoirs alimentés par des sources d'énergies renouvelables. Project CRAT/PRO/304. Report.

Duffie, J.A., Beckman, W.A. 1980. Solar engineering of thermal processes. John Wiley and Sons, New York, NY, USA.

Gnininvi, M. 1981. Séchage solaire dans les projets de développement communautaire (Rapports 1, 2 et 3 à USAID/Lomé 1979-1981). Laboratoire sur l'énergie solaire. University of Benin, Lomé, Togo.

Gnininvi, M., Kerim, B. 1983. Étude comparative du séchage des cossettes de manioc dans l'enceinte solaire et à l'air libre. Paper presented at the Nairobi/Rosta Seminar, November 1983.

Gnininvi, M., Amouzou, K., Kerim, B. 1985. Field tests of a two-tonne maize solar dryer. Paper presented at the International Conference on Research and Development on Renewable Energy Technologies in Africa. Mauritius. March 1985.

Herbert, J.P., Gaiffon, D., and Themelin, A. 1984. Utilisation de l'énergie solaire pour le séchage de produits agricoles dans les pays en voie de développement. Paper presented at the Solar Energy Seminar, Trieste, Italy, September 1984. Paper 4.

Thompson, B.W. 1970. The climate of Africa. Oxford University Press, Nairobi, Kenya.

Tollier, M.T., Guilbot, A. 1973. Évolution de certains constituants du maïs en fonction de diverses conditions de séchage et stockage. Paper presented at the International Symposium on Conservation des grains récoltés humides, March 1973, Paris, France.

Wallace, B., Michael, J., Morgan, A.I. 1973. Food dehydration, drying methods and phenomena (Vol. 1). Avi Publishing Co., Westport, CN, USA.

Appendix: Comparison of Solar with Fuel- and Charcoal-Fired Dryers

Net Energetic Efficiency

The test results on drying 2000 kg of maize in the Tabligbo dryer (Table 4) show that the physical drying limit was reached after 4 days but that the useful drying period only extended to the end of the 2nd day when the average net efficiency was 15% (Table 7). The energy efficiency decreased from 18% on the 1st day to 1% on the 4th (Table 7).

In an industrial operation, drying can be stopped when the moisture content is comparable to the ambient relative humidity of the storage environment -- that is, 13% moisture content -- which was reached on the 2nd day.

Table 7. Energy balance for drying maize grain over 6 days.

	Day						
	0	1	2	3	4	5	6
Moisture content (%)	20.3	16.1	13.2	12.0	11.8	13.1	12.2
Water evaporated (kg)	-	84	58	24	4	-26	18
Useful energy (kWh)	-	63	44	18	3	-20	14
Net efficiency (%)	-	18	12	5	1	-6	4

Q evaporation = 635 kcal/kg water = 2.7 MJ/kg = 0.75 kWh/kg.
1 tep = 11.86 mWh.

Table 8. Comparison of solar, fuel-fired, and charcoal-fired drying systems.

	Solar dryer							
	Wooden		Cement		Fuel-fired		Charcoal-fired	
Costs (USD)	Full capacity	14% capacity	Full capacity	14% capacity	Full capacity	14% capacity	Full capacity	14% capacity
Equipment	7000		14000		7500		5500	
Fuel	-		-		14760	2066	7068	990
Fixed costs								
Interest[a]	13887		15105		11400		8364	
Labour[b]	5000	700	5000	700	8000	1120	13000	1820
Repairs and replacement[c]	14000		7000		7500		5500	
Total	39887	35587	41105	36805	49160	29586	39432	22174
Cost/tonne[d]	7.3	46.2	7.5	48.0	8.9	38.3	7.1	28.8
% product value[e]	4.8	30.8	5.0	31.9	6.0	25.6	4.7	19.2

[a] Interest of 10% per year on equipment and replacements.

[b] Labour (hours/day per tonne): 3 for solar dryers; 5 for fuel-fired dryers; and 8 for charcoal-fired dryers.

[c] Repairs/replacement: twice in 15 years for wooden solar dryer; maintenance only for cement solar dryer; and once every 15 years for fossil fuel and charcoal dryers.

[d] Based on assumed production of 5500 t dried in 15 years at full capacity or 770 t dried at 14% capacity, i.e. 4600 hours total.

[e] Based on a harvest value of 150 USD/t for maize.

Cost Comparison

If we assume a nominal drying capacity of 2 t in 2 days (or 1 t/day), optimal usage (i.e., uninterrupted operation for 15 years), a collector area of 81 m^2, and a solar intensity of 4.4 kWh/m^2 per day (the average for June to September in Togo), the primary energy collected is:

Years x Days/year x kWh/m^2 per day x m^2
15 365 4.4 81 = 1.95 gWh.

Because the efficiency of the solar dryer was 15% (over the 2-day drying period), only 0.29 gWh of useful energy would be produced over the 15-year life of the solar danger. A fuel-fired system with an efficiency of 60% would consume 0.49 gWh of energy (41 t of fuel at a cost of USD 360/t) to produce 0.29 gWh of useful energy and a charcoal-fired system with an efficiency of 40% would consume 0.73 gWh of energy (62 t of charcoal at a cost of USD 114/t).

These fuel values can then be used in comparing the costs of various dryers (Table 8). If uninterrupted operation is assumed, solar dryers compare favourably with other types of dryer. The additional costs are still below the threshold of 5% of the value of the product at harvest.

In actual circumstances, where usage is intermittent, say 14% or about 51 days of use per year, all the systems studied here are economically unacceptable for low market-value products such as maize or cereals. Even in this case, depending on geographic location, charcoal-fired dryers may be preferable to fuel-fired dryers.

RESEARCH AND DEVELOPMENT ON SOLAR DRYING: ADVANCING ENERGY SUPPLY OPTIONS OR MEETING FELT NEEDS

Charles Y. Wereko-Brobby[1]

Abstract — *The major attraction of solar dryers to Africa in the decade 1974-84 was the potential to act as the vehicle for solving two of the continent's most urgent socioeconomic problems: a growing crisis of insufficient food production to feed a rapidly rising population; and the severe economic recessions brought on by the rapid increases in fossil fuel prices over the same period. However, because the development of improved solar dryers was largely a consequence of the energy problems of the 1970s, the basic issues and perception of relevant solutions must be set firmly in a framework of increasing energy supply options, especially from indigenous sources. The result has been that the basic research problem is conceived primarily as one of developing better energy technologies that will implicitly solve the postharvest loss problems. Almost all of the research and development (R&D) that has taken place has been defined and executed by technologists, usually engineers. Their primary objective has been to improve the thermodynamic performance of dryers, thus increasing the energy supply options for the rural areas. The efforts have turned up several designs that are technologically superior to traditional sun drying. Nevertheless their appropriateness as solutions to postharvest problems are yet to be substantiated, and in many cases the improved dryers are not applicable in most of rural Africa. This paper discusses the major issues and factors that must be considered in the conceptualization, definition, and execution of R&D projects on solar crop dryers in Africa. It proposes a possible conceptual framework for assessing the relevance, desirability, viability, and technoeconomic feasibility of projects to ensure their developmental and scientific credibility.*

Introduction

The first African Energy Programme (AEP) Conference took place in March 1985 and was dominated by presentations of papers on the results of numerous research and development (R&D) projects to develop better solar crop dryers for use in Africa (CSC 1986). The papers demonstrated that Africa has acquired the technical capabilities to design, test, and evaluate technologically superior methods of drying food and agricultural products. However, it was also very apparent that much of the effort had taken place in the context of ill-defined or peripheral consideration of the development problems that formed the basis of the research work. (Indeed, this perception was so strong that it formed the theme of an immediate informal workshop held aboard a West Africa-bound flight: the pity was that the discussion was perhaps 6-7 hours late.) Nevertheless, the essence of the discussion of this paper, and indeed of any proposed investigation of solar crop dryer development in Africa, is how to obtain apropriate answers to the following four questions.

---

[1] Commonwealth Science Council, London, United Kingdom. The views expressed are those of the author and not necessarily those of the Commonwealth Science Council.

- What is the primary objective of the research project? To provide energy, to improve the commodity supply, or both?
- Who are the intended beneficiaries? Individuals, companies, or a target welfare group?
- What are the alternative options for meeting the stated objectives; in terms of the relative costs and efficacy of both technologies and energy supply sources?
- What should be the constituent elements of an appropriate R&D program to ensure a viable and beneficial output from a project?

These questions are discussed against the backdrop of the experiences of the Solar Crop Drying Project (SCDP) of the AEP, established by the Commonwealth Science Council (CSC) in 1979 with the expressed objective (CSC 1980): "to improve traditional methods of sun drying crops and commodities in Africa by the development and introduction of appropriate solar drying techniques."

Defining the Research Problem

The specific objectives of the AEP-SCDP were "to design, develop and test solar dryers for small- and large-scale farmers, including cooperative societies." Although regional in nature, each component project was to take account of the special needs of the individual participating countries, both in terms of target commodities and user-groups. Thus, the problem under investigation was defined clearly as technological innovation to ameliorate the deleterious effects of the oil crisis. What was not readily apparent nor explicitly stated was the nature and scale of the end-users' problems that the improved technologies would solve, and what the costs were in relation to other possible courses of action. The implicit assumption was that, given the acute energy supply situation, any development of an alternative supply source was desirable and likely to benefit all end-users.

The prerequisite for embarking on a solar drying R&D project is the establishment of a case for drying as a postharvest process. Where such drying is already the practice, with natural sun drying or the use of fuel-driven drying technologies, or both, the major research thrust can be very clearly defined. Such was the case for all the AEP projects (Table 1). However, the identification of the research thrust is not by itself an adequate indicator of the relative importance nor of the size of the problems to be solved. The drying

Table 1. Commodities for African Energy Programme solar drying projects.

Country	Commodities	Target groups
Gambia	Rice, fish	Small-scale, rural
Ghana	Peppers, cassava chips, maize, bean, fish	Small-scale, rural
Kenya	Coffee, tea, pyrethrum Maize Maize	Commercial farmers Small-scale, rural Cooperatives
Mauritius	Multicrops	Small-scale
Tanzania	Pyrethrum Fish	Commercial farmers Small-scale, rural
Uganda	Corn, soybeans, peanuts, fish, coffee	Commercial farmers
Zimbabwe	Seasonal vegetables	Small-scale, rural

Source: Based on information in CSC (1982).

process is only one stage in the postharvest process, which, for example in grains, encompasses harvesting, handling, threshing, drying, storing, and milling.

Thus, an essential first task is establishing the relative importance of drying within the postharvest processes for a given commodity. In other words, the extent of postharvest loss must be translatable into measurable indicators of economic, quantitative, qualitative, and nutritional quantities as a key element of the problem-definition process to establish the boundary conditions for the drying research program.

Many of the important specific questions to be asked have been included in a recent handbook (CSC 1985). Nevertheless, some of these bear repeating and are relevant here:

- The quantity of commodity produced in a harvesting period or season in the target areas;
- The nature and numbers of producers of each of the target commodities;
- The estimation of total postharvest losses, including those attributable to drying;
- An assessment of the adequacy of existing drying methods and potentials for improvements;
- The market and price relationships of the commodity, including seasonal variations, value-added effects of drying, and potential demand for increased productions; and

- The relative costs of current drying methods in relation to the income and expenditure levels of the target groups.

For the enthusiastic technological researcher, answers to these questions should help to identify the most important areas for research innovation to reduce postharvest losses. For example, although there are very few sources of information on loss distribution among various crops, one study of rice postproduction in Southeast Asia (de Padua 1974) gives, as typical for that region, the breakdown shown in Table 2.

Because the loss percentages at various stages are cumulative, perhaps the most challenging problem for postharvest technological innovation, at least in Southeast Asia, may be for improved storing and milling, with drying being third in importance. The point is that, although values for rice-loss distribution in Africa may be different, one can establish the relative importance of improved drying on the basis of the four evaluative indicators without having basic information similar to that given by de Padua (1974).

Of course, where drying is a major postharvest activity, such as for pyrethrum, it may not be necessary to make the case for improved drying. Nevertheless, it is still important to determine the basic information on existing drying practices to be certain that the improvements being sought are best achieved by improved solar technologies. The greatest loss may be attributable to the harvesting and purchasing policies in place. Thus, for example, a shift in policy from a purchase of product from subsistence farmers to centralized purchases of wet produce, which is then dried under high quality-control conditions, could reduce drastically the postharvest losses in pyrethrum production. This, in fact, was the case in Tanzania. Here, the research problem was reduced to one of how best to provide the energy source for the controlled drying. Even in this case, it is still important to qualify the drying problem so as to be able to assess the value-added benefits of a switch in purchasing procedures as well as to obtain a target figure for acceptable costs of any proposed drying technology. In other words, if the problem can be reduced to a consideration of energy supply options, the minimum target costs of alternative sources must be those that maintain the value of the dried crop. That is, if the solar option costs are much

Table 2. Rice postharvest loss estimates for Southeast Asia based on a 100-kg harvest.

Stage	**Percentage loss**	**Residual product weight (kg)**	**Actual weight loss (kg)**
Harvesting	1-3	97-99	1-3
Handling	2-7	90-97	2-9
Threshing	2-6	85-95	2-12
Drying	1-5	81-94	5-14
Storing	2-6	76-93	3-18
Milling	2-10	68-90	3-25

Source: Adapted from de Padua (1974).

greater than the value of the "saved" products, the solution offered is inappropriate even if the scientific or technical innovation is the best.

At the heart of the process of defining research problems is the question implicit in the title of this paper, and each research team must establish a credible case for a strategy that focuses on improved solar drying technologies. The task may be easier in some cases than others, such as searching for alternatives to existing mechanized energy supply options where commercial judgments of viability are reduced to the technoeconomic competitiveness of various options. Where this is not so obvious, especially when dealing with subsistence farming communities in the informal economic environment, the technological innovation option can only really be considered as the last stage in the process of research problem definition. Indeed, the need for this approach assumes a far greater importance now that the "oil crisis" bogey has been turned on its head, and we can no longer assume our self-appointed roles as "leaders on the path to a new and brighter energy future."

Targeting the Beneficiaries

The impetus for the massive increase in development of solar dryers was the market supply and price problems of oil in the 1970s. Because of this, governments in many developing countries, international funding agencies, and researchers operated on the single assumption that any activity that increased, or diversified, energy supply options would be good for the country in the long run. Thus, it was not so necessary to establish the socioeconomic case for developing renewable energy technologies: this was self-evident. The task was to develop innovative technological solutions quickly and all would be well in the future.

In spite of the massive injection of human, institutional, and financial resources into technological demonstrations, however, it was always clear that each country would, in the end, have to make choices as to which technology best aided its socioeconomic developmental objectives, especially where several of these demonstrated a potential to reduce the country's reliance on imported energy sources. Implicit in this general thesis was the unfortunate conclusion that oil-exporting countries did not need to take a serious look at research on renewables because of their secured energy-supply base.

However, notwithstanding the climate that spawned the R&D activities, the prime consideration of any target group in its decision-making process is that of the optimum organization and utilization of available resources to satisfy stated objectives. This is true of countries as a whole, concerned with overall group welfare, through to business enterprises and individuals interested in maximizing their wealth, either as profits or improved quality of life.

For governments, the objective of supporting solar dryer R&D may be either to seek alternative, and usually indigenous, sources of energy for both current and prospective socioeconomic objectives, or it may even have the altruistic objective of seeking to improve both the quantity and quality of food supply in the rural areas of the country. Whichever objective is sought will have to be evaluated in the context of its optimum resource utilization and, because group-welfare quantification is fraught with uncertainties, it is usual to seek this through the more easily quantifiable target groups of business or individuals. Thus, even though much of the R&D will be government funded, the target group should be well defined: large-scale commercial farmers, small-scale rural subsistence farmers, and rural cooperative farming groups (Table 1).

Whatever the composition of the target group, the potential attraction of solar dryers will be influenced by the following questions:

- Will the solar dryer increase the target group's outputs for the same inputs, e.g., reduce postharvest losses through more efficient drying?
- If new investments have to be made to obtain greater benefits from the novel solar dryer, would the additional returns be greater than the required investment, i.e., would there be the markets for the extra produce from the solar drying process?
- If the target group is already deriving optimum benefits from their existing activities, would an investment in solar dryers increase their wealth further by opening up new opportunities, e.g., could the improved technology provide an opportunity for increasing primary production or even offer new avenues for benefits such as offering spare drying capacity to other producers?

Underpinning these considerations is the reality that the target groups' perception of the worth of a solar drying technology is not derived necessarily from its potential for energy conservation or import substitution. It is based primarily on the expected opportunities for greater generation of wealth. The energy supply option only becomes relevant in a situation where the new technology substitutes directly for a less cost-effective alternative. Of course, the measure of cost-effectiveness could include considerations of improved benefits from an assured energy supply offered by the solar option. Thus, for many commercial farmers already employing some form of fuel-driven mechanized drying technology, the extent of fuel-supply security, including increasing costs, could shape their own perceptions of a national energy crisis.

The message is that technologists must present attractive solutions to the target groups and the basis of that attraction must be largely that perceived by the target groups and not by the researchers. It would be pointless to offer sophisticated, mechanically driven dryers to farmers who have relied predominantly on sun drying unless the potential benefits of increased investments and operational sophistication are readily apparent. By the same token, it will not be necessary to undertake a very detailed technoeconomic feasibility appraisal when designing for fuel-substitution in a commercial farming situation. Here the requirement would be to appraise the full costs and expected benefits and only to proceed where the potential benefits exceed the costs of additional investments for technological innovation.

The following case study provides an illustration of some of the major issues raised in this section.

Case Study

A medium-scale rural farmer produces 5000 kg of maize per year, which is dried to a storage moisture content of 13.0% at a temperature of 27°C. The market price for maize is $10.00/kg and the retail price of fuel oil is $2/L, and increases by 10% each year. (Note: although the dollar symbol is used, monetary units are in no particular currency.) The annual consumption of fuel is 500 L. The farmer employs a mechanical dryer driven by fuel oil. However, because of the steep increases in prices and the increasingly unreliable supply of fuel, the farmer is attracted by the prospect of solar dryers as an alternative means of drying his produce. Two designs are offered: the first, a natural-convection device that, for a capital cost investment of $10,000, will substitute for the oil-fired dryer; the second is a photovoltaic-powered forced-convection device costing $50,000 but capable of drying up to 7500 kg of maize.

The farmer has two options of using the spare capacity of the sophisticated dryer:

- To increase his annual production to 7500 kg at a further investment of $5000/year; or
- To lease out the capacity to other producers at a rate of $3/kg.

The simpler dryer is constructed entirely of local materials and thus the national Agricultural Development Bank is allowed to offer purchase loans at a discount rate of 8%, compared with a national average of 10%. However, the modules for the photovoltaic system must be imported and the discount rate of the purchase loan is set at 15%. On the other hand, because the second dryer offers the prospect of increased grain production, reducing current imports, the Ministry of Agriculture is offering a grant of $9500/year to the farmer if he increases his own production and $4500/year if it is made available for the use of other farmers. The annual operating and maintenance costs for the dryers are $500 for the conventional and natural solar dryers and $1500 for each of the forced solar dryers.

The economic life of the simple dryer is 12 years (equal to that of the useful economic life of the mechanical system) and that of the photovoltaic system is 15 years. All equipment is assumed to have no residual value at the end of its operational life.

Which of the four available options to the farmer would bring the most benefits to him?

Solution

To take account of the time value of money, an important factor in considering long-range project feasibility appraisals, the net present value (NPV) approach is used to discount all expected costs and benefits for each operating year of the project. The NPV method assumes that there is a minimum desirable discount rate that makes the project acceptable. All future cash flows are discounted to the present at the set rates and the project with the largest NPV is selected as the most desirable (see CSC 1986, chapter 19).

Using the basic operational and financial data for the four drying options (Table 3), NPVs of the various options have been determined (Table 4) at the appropriate discount rates using discount factors derived from standard tables.

The appraisal shows that the photovoltaic-powered dryer (forced solar) used to increase the farmer's production would bring the greatest benefits ($431,089), even though it also requires the largest investment in equipment and increased production facilities. The second best option is the natural solar dryer ($363,032) and may be worth considering if the farmer is unable to raise the necessary collateral for the larger loan. The leased capacity forced solar

Table 3. Operational and financial data for various dryer options.

	Dryer options			
			Forced solar	
	Conventional	Natural solar	Increased production	Leased capacity
Product yield (kg)	5000	5000	7500	7500
Product sales ($)	50000	50000	75000	50000
Annual incentives ($)	--	--	9500	4500
Other income ($)	--	--	--	7500
Equipment capital cost ($)	--	10000	50000	50000
Annual operating costs ($)	500	500	1500	1500
Fuel consumption (L)	500	--	--	--
Equipment life (years)	12	12	15	15
Discount rate (%)	--	8	15	15
Annual rate of fuel price increase (%)	10	--	--	--
Equipment residual value ($)	0	0	0	0

Table 4. Net present values of various options.

Option	Net present value ($)
Conventional dryer	326,372
Natural solar dryer	363,032
Forced solar dryer	
Increased production	431,089
Leased capacity	328,762

Source: Appendix, Tables 6-9.

dryer option presents a marginal advantage over the conventional fuel-oil fired system ($328,762 against $326,372). Thus, it is arguable whether the farmer could be persuaded to switch from fossil fuel to solar power on the basis of a perceived national fuel shortage, especially as the benefits from the additional investments are so small compared with the costs, risks, and technological complexity of a switch to a leased solar-powered forced dryer.

In the end, all national priorities must be translatable into tangible benefits that can be expressed in fiscal terms so that the targeted individuals or groups can make their choices on their perceived gains from various options. The issues for consideration in such an evalution are several and quite complex, of which improvements in energy technological efficiency is only one. The social and economic environment in which the technology fits must be well defined and understood to establish the relative usefulness of the technological innovation.

R&D to Meet Felt Needs

This discussion has attempted to highlight the importance of establishing an appropriate contextual framework for defining and resolving those postharvest drying problems perceived by the targeted user groups. The key to success and relevance lies in the existence of a well-defined R&D strategy and especially in the blend of human skills employed at each stage of the exercise. So far, technologists have been the prime motivators of R&D endeavours on solar crop drying, and indeed will be expected to make substantial contributions to any solutions based on technological innovation. However, unless the technologists' skills and talents are focused and targeted at specific elements of what is a multifaceted problem, the results will almost certainly be the evolution of technologies in search of ill-defined or nonexistent problems.

The potential skills of the technologist must be incorporated within a multidisciplinary team in which the leadership role at each stage of the R&D process is determined by the specific objective functions being addressed (Table 5). In setting up a conceptual framework for an R&D strategy for solar drying work, the objective functions of each stage must match an appropriate research team and the key members or skills for the particular task must be identified.

Such a framework is almost certainly contentious and will no doubt be subjected to severe scrutiny both in the ordering of the stages and in the implied importance of different skills at various stages. Nevertheless, it must be attempted as a necessary prerequisite for establishing an R&D program on solar drying that will meet the felt needs of target groups and, at the same time, offer the scientific challenge and excitement of innovation to the technologists. A strategy based on the assembly and optimum utilization of specialized skills within a multidisciplinary research team is the best way to ensure that a program does not result in the unfortunate, but far too frequent, derived result of a brilliantly innovative and technologically superior dryer, if only the target groups would alter their needs to fit it or if the required investments could be brought within reach of the income levels of the target groups.

Table. 5. Conceptual framework for R&D on solar crop drying.

Stage	Objective function	Engineers	End-users	Industrialists	Economists	Sociologists	Agriculturalists	Extension workers	Planners	Biochemists	Entrepreneurs	Food scientists
1	Postharvest investigations	K	K		0	K	L	0				
2	Targeting user groups	0	K	K	L	K	0	0	L			
3	Establishing baseline data on crop characteristics and drying parameters	L	0				0			K		K
4	Design and evaluation of experimental prototype technologies	L	K	K	0	0		0				
5	Field testing and evaluation of industrial prototypes	L	0	K	K	0		0				
6	Manufacture and dissemination of industrial dryers	0	K	L	0						K	

[a] L = stage leader; K = key members of team; and 0 = other members of team.

Acknowledgement -- I acknowledge the financial support of the Commonwealth Science Council and the British Overseas Development Administration.

References

CSC (Commonwealth Science Council). 1980. African Energy Programme Project Group Meeting, 20-26 September 1979, Anoha, Tanzania. CSC, London, U.K. AEP Reports 1 and 2.

____________ 1982. African Energy Programme Workshop on Solar Crop Drying, 11-13 October 1982, Nairobi, Kenya. CSC, London, U.K. AEP Reports 8 and 9.

____________ 1985. Solar dryers: Their role in post-harvest processing. CSC, London, U.K.

____________ 1986. Renewable energy development in Africa: Proceedings of the international conference on R&D for renewable energy technologies in Africa, 25-29 March 1985. CSC, London, U.K.

De Padua, D.B. 1974. Post-harvest rice technology in Indonesia, Malaysia, The Philippines, and Thailand: A state of the art survey. International Development Research Centre, Ottawa, Ont., Canada.

Appendix: Source tables for case study

Table 6. Net present value analysis[a] in arbitrary monetary units for forced solar dryer with increased production.

Year	Capital costs	Operating costs	Total costs	Total benefits	Net benefits	Discount factor	Present value
0	25000	-	25000	0	-25000	1.0000	-25000
1	5000	8000	3000	75000	78000	0.8696	67829
3	5000	8000	3000	75000	78000	0.7561	58976
4	5000	8000	3000	75000	78000	0.6575	51285
5	5000	8000	3000	75000	78000	0.5718	44600
6	5000	8000	3000	75000	78000	0.4972	38782
7	5000	8000	3000	75000	78000	0.3759	29320
8	5000	8000	3000	75000	78000	0.3269	25498
9	5000	8000	3000	75000	78000	0.2843	22175
10	5000	8000	3000	75000	78000	0.2472	19282
11	5000	8000	3000	75000	78000	0.2149	16762
12	5000	8000	3000	75000	78000	0.1869	14578
13	5000	8000	3000	75000	78000	0.1623	12675
14	5000	8000	3000	75000	78000	0.1413	11021
15	5000	8000	3000	75000	78000	0.1229	9586

[a] Total costs = Capital costs + Operating costs; Net benefits = Total benefits - Total costs; Present value = Net benefits x Discount factor.

Table 7. Net present value calculation in arbitrary monetary units for conventional dryer.

Year	Fuel costs per litre	Operational costs	Net benefits	Discount factor	Present value
0	-	-	-	1.0000	-
1	2.00	1500	48500	0.9091	44091
2	2.20	1600	48400	0.8264	39998
3	2.42	1710	48290	0.7513	36280
4	2.66	1831	48169	0.6830	32899
5	2.93	1963	48037	0.6209	29826
6	3.22	2112	47888	0.5645	27033
7	3.54	2271	47729	0.5132	24495
8	3.87	2441	47559	0.4665	22186
9	4.28	2640	47360	0.4241	20085
10	4.71	2855	47145	0.3855	18174
11	5.18	3090	46910	0.3505	16442
12	5.70	3350	46650	0.3186	14863

Table 8. Net present value calculation in arbitrary monetary units for natural solar dryer.

Year	Net benefit	Discount factor	Present value
0	-10000	1.0000	-10000
1	49500	0.9259	45832
2	49500	0.8573	42436
3	49500	0.7938	39293
4	49500	0.7350	36383
5	49500	0.6806	33690
6	49500	0.6302	31195
7	49500	0.5835	28883
8	49500	0.5403	26745
9	49500	0.5002	24760
10	49500	0.4632	22928
11	49500	0.4289	21231
12	49500	0.3971	19656

Table 9. Net present value calculation in arbitrary monetary units for forced solar dryer with leased capacity.

Year	Net benefit	Discount factor	Present value
0	-25000	1.0000	-25000
1	60500	0.8696	52611
2	60500	0.7561	45745
3	60500	0.6575	39779
4	60500	0.5718	34594
5	60500	0.4972	30081
6	60500	0.4323	26154
7	60500	0.3759	22742
8	60500	0.3269	19777
9	60500	0.2843	17200
10	60500	0.2472	14956
11	60500	0.2149	13001
12	60500	0.1869	11307
13	60500	0.1625	9831
14	60500	0.1413	8549
15	60500	0.1225	7435

WORKSHOP PARTICIPANTS

Sabiba Kou'santa **Amouzou,** Laboratoire sur l'Énergie Solaire, Institut National des Sciences de l'Éducation, Université du Bénin, B.P. 1515, Lomé, Togo

Edwin A. **Arinze,** Department of Agricultural Engineering, Faculty of Engineering, Institute for Agricultural Research, Ahmadu Bello University, PMB 1044, Zaria, Nigeria

Michael W. **Bassey,** Agriculture, Food and Nutrition Sciences Division, International Development Research Centre, Box 11007, CD Annexe, Dakar, Senegal

Modibo **Dicko,** Laboratoire de l'Énergie Solaire, B.P. 134, Bamako, Mali

Niokhor **Diouf,** Division Poisson, Institut de Technologie Alimentaire, B.P. 2765, Dakar, Senegal

Paul **Fleming,** Solar Energy Technology Centre, School of Mechanical Engineering, Cranfield Institute of Technology, Bedford MK43 0AL, United Kingdom

Messan Kokou **Gnininvi,** Laboratoire sur l'Énergie Solaire, Institut National des Sciences de l'Éducation, Université du Bénin, B.P. 1515, Lomé, Togo

Joseph C. **Igbeka,** Department of Agricultural Engineering, Faculty of Technology, University of Ibadan, Ibadan, Nigeria

Ernest **Kaptouom,** Laboratoire de Mécanique et Énergétique, École Nationale Supérieure Polytechnique, B.P. 8390, Yaoundé, Cameroun

Edward **Koroma,** Rice Research Station (Rokupr), PMB 736, Freetown, Sierra Leone

Hyacinthe **Mbengue,** Centre National de Recherches Agronomiques, B.P. 53, Bambey, Senegal

Charles **Minka,** Department of Renewable Energies, National Center for Studies and Experimentation in Agricultural Mechanization (CENEEMA, Centre national d'études et d'expérimentation du machinisme agricole), P.O. 1040, Yaoundé, Cameroon

Geoffrey Christopher **Mrema,** Department of Agricultural Engineering, Sokoine University of Agriculture, Box 3003, Morogoro, Tanzania

Adi **N'Jai,** Fisheries Department, Banjul, The Gambia

P.H. **Oosthuizen,** Department of Mechanical Engineering, Queen's University, Kingston, Ontario, Canada K7L 3N6

Herick **Othieno,** Kenyatta University College, Appropriate Technology Centre, P.O. Box 43844, Nairobi, Kenya

Ozzie **Schmidt,** Agriculture, Food and Nutrition Sciences Division, International Development Research Centre, P.O. Box 62084, Nairobi, Kenya

Frank B. **Sebbowa,** Department of Mechanical Engineering, University of Nairobi, P.O. Box 30197, Nairobi, Kenya

Alpha **Sheriff,** Department of Mechanical Engineering, Queen's University, Kingston, Ontario, Canada K7L 3N6

Charles **Speirs,** Industrial Development Department, Tropical Development and Research Institute, Culham, Abingdon, Oxfordshire, OX14 3DA, United Kingdom

Charles **Wereko-Brobby,** Commonwealth Science Council, Marlborough House, Pall Mall, London, SW1Y 5HX, United Kingdom

Malcolm **Whitfield,** Department of Mechanical Engineering, Fourah Bay College, University of Sierra Leone, Freetown, Sierra Leone

Yahaya **Yaou,** Office de l'Énergie Solaire, B.P. 621, Niamey, Niger

Y.K.L. **Yu Wai Man,** School of Industrial Technology, University of Mauritius, Reduit, Mauritius

IDRC staff

Gilbert **Croome,** Communications Division, International Development Research Centre, P.O. Box 8500, Ottawa, Ontario, Canada K1G 3H9

Jean-Daniel **Dupont,** Communications Division, International Development Research Centre, P.O. Box 8500, Ottawa, Ontario, Canada K1G 3H9

Rose-Marie **Erambert,** Agriculture, Food and Nutrition Sciences Division, International Development Research Centre, Box 11007, CD Annexe, Dakar, Senegal

Marie Elizabeth **Turpin,** Agriculture, Food and Nutrition Sciences Division, International Development Research Centre, Box 11007, CD Annexe, Dakar, Senegal

Head Office
IDRC, P.O. Box 8500, Ottawa, Ontario, Canada K1G 3H9

Regional Office for Southeast and East Asia
IDRC, Tanglin P.O. Box 101, Singapore 9124, Republic of Singapore

Regional Office for South Asia
IDRC, 11 Jor Bagh, New Delhi 110003, India

Regional Office for Eastern and Southern Africa
IDRC, P.O. Box 62084, Nairobi, Kenya

Regional Office for the Middle East and North Africa
IDRC/CRDI, P.O. Box 14 Orman, Giza, Cairo, Egypt

Regional Office for West and Central Africa
CRDI, B.P. 11007, CD Annexe, Dakar, Senegal

Regional Office for Latin America and the Caribbean
CIID, Apartado Aéreo 53016, Bogotá, D.E., Colombia

Please direct requests for information about IDRC and its activities to the IDRC office in your region.